Assessing the representation of TCs in global models:

A brief overview of the past
Some current and future work

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Outline

- Motivation for this study
- Overview: what *past and current models* in *weather-forecasting mode* or *free-running mode* can do in terms of Tropical Cyclone vertical structure, scale, intensity, track realism, genesis process, large-scale forcing
- Model comparison in forecast mode: MRF NMC, NASA GEOS-4, NCEP GFS (2004); NASA GEOS-5 v2 (with relaxed Arakawa-Schubert)
- Model comparison in long simulations: ECMWF T511 Nature Run, GEOS-5 (with stochastic Tokioka and same experimental settings as the ECMWF NR)

Motivation

- Fact: Some Tropical cyclone features commonly appear in operational global models (vertical alignment, warm core, low-level convergence, upper-level divergence, *very deep* center pressures).
- Questions: How realistic are they? How comparable are they? Can we quantify this realism?

TCs in high-resolution global models

- It has been *empirically noted* in the operational wx forec. community that at hor. res. of 1 degree one can start seeing vertically aligned structures and an eye-like feature, at 0.5 degree the maximum winds begin to develop in the lower levels (instead of the mid-troposphere, as observed in lower resolution global models), at resolutions of few tens of kilometers global models start displaying realistic radii of maximum wind (e.g., *Atlas et al., 2005; Shen et al., 2006; Reale et al., 2007*),
- But it takes *cloud-resolving models* at resolution of few kilometers to detect eye-wall replacement cycles
- Accepting the limitation imposed by global models, the problem which we are trying to address in this work is the optimal representation of a tropical cyclone at a given resolution.

Is high resolution always exploited?

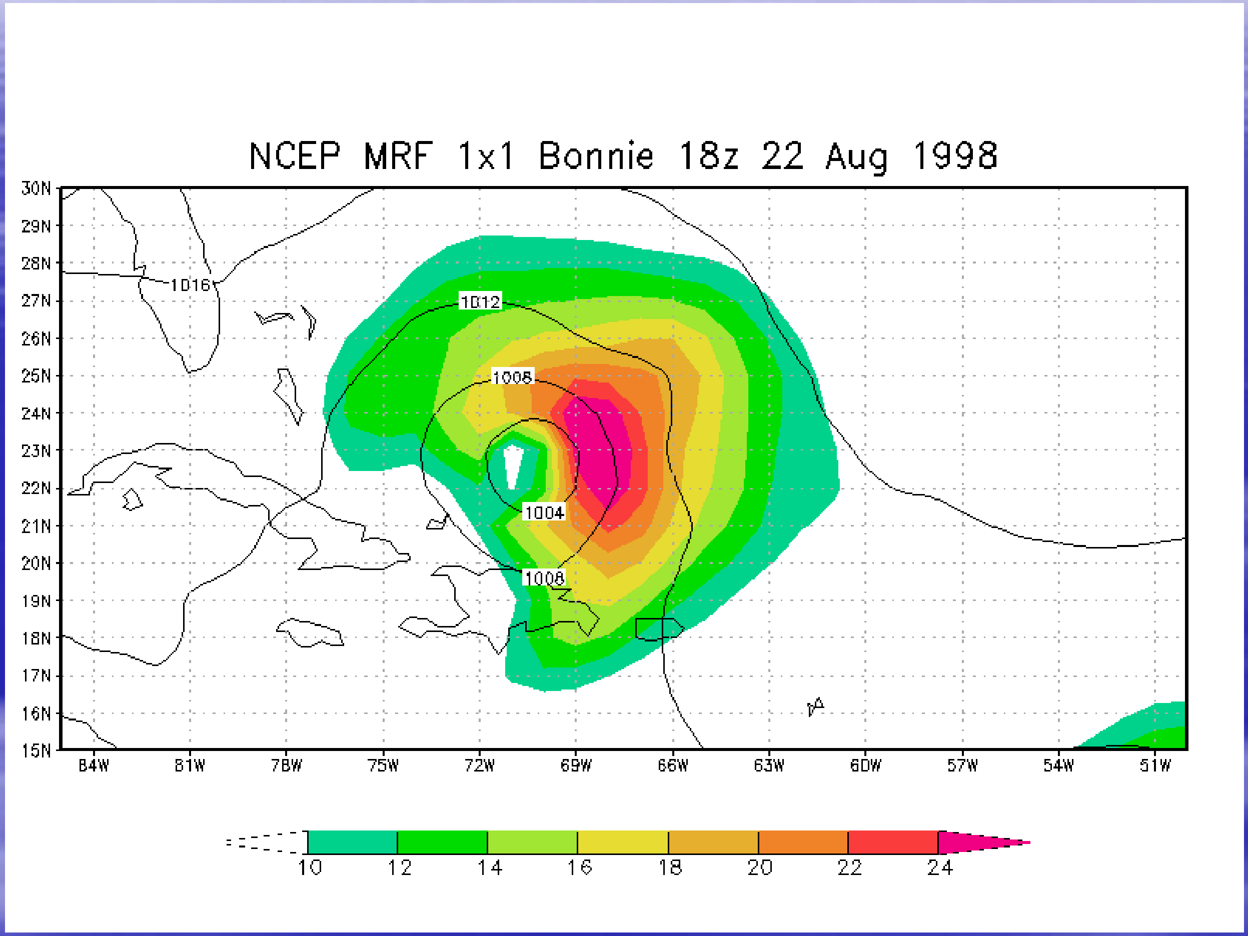
- At any resolution, a wind speed vertical cross-section of a *mature* tropical cyclone should present two approximately symmetric maxima around a wind minimum.
- The compactness of this eye-like feature increases with resolution but occasionally high resolution models display structures that are *much broader* and *more diluted* than what could be expected at that resolution.
- For example, unrealistically large eye-like features (on the order of hundreds of km, encompassing several gridpoints) are common in GCMs even when resolution is high, such as quarter of a degree.
- In other words, it does not seem that the optimal, theoretical representation that should be possible at a given resolution, is always reached.

TCs in Global Operational forecasting models

- Evaluating causes of forecasting track failures in global operational models on a weather forecasting time-scale is relevant also for climate studies: it may help understanding processes that can be erroneously represented in long simulations
- In latest global operational models forecast, structure realism and good forecast track appear to be connected (unlike the past, where track and intensity were treated as *completely separate* problems)
- The quality of the representation of some large-scale forcings (i.e. ITCZ position) appear to control part of the weather forecasting scales involved with TC motion
- In the past (>10 years), TC representation in global operational models was sporadic and very poor
- Bogusing was a necessity (now replaced by vortex relocation)

11 years ago: Bonnie (1998)

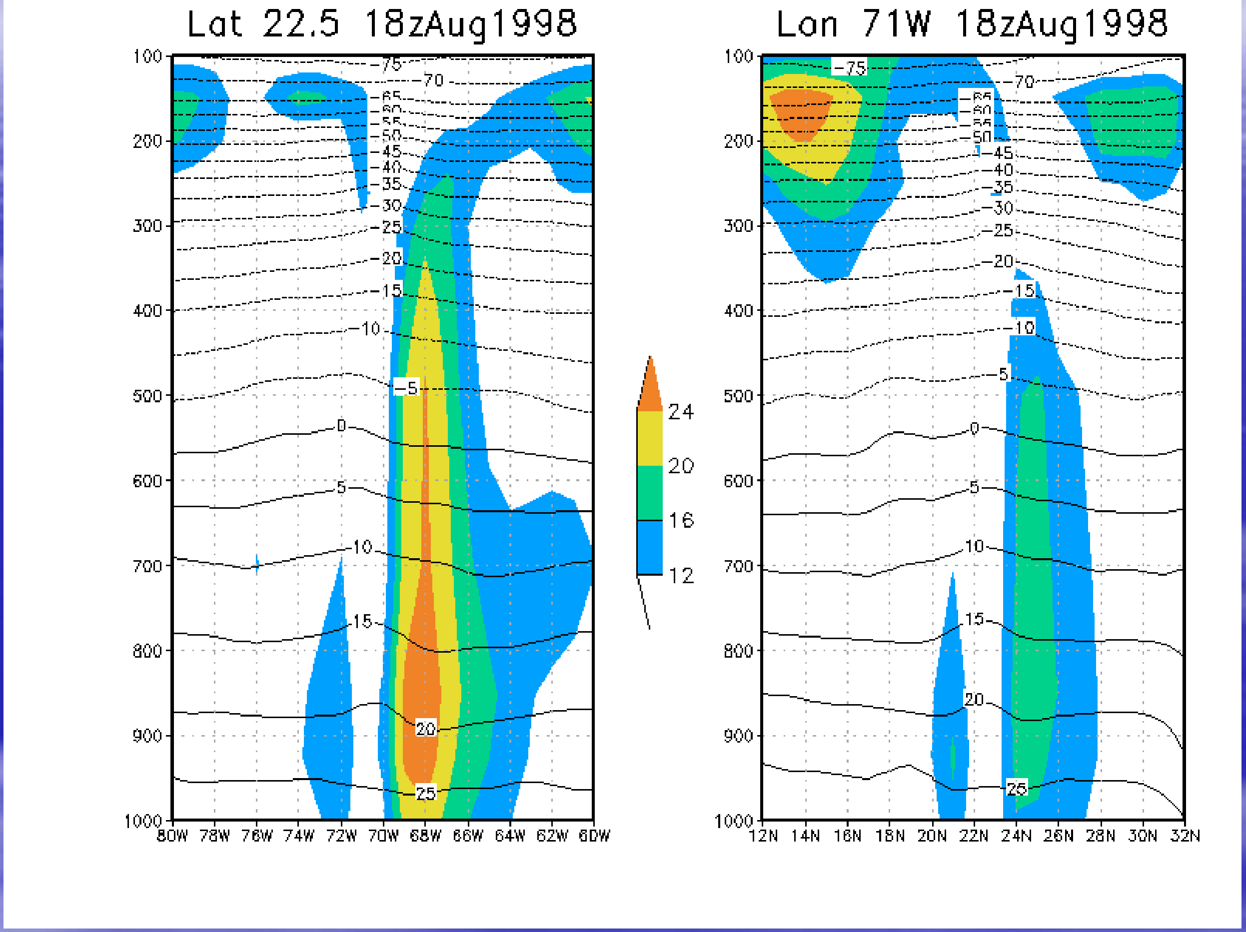
as seen by the MRF (ancestor of NCEP GFS)



850 hPa wind
Sea level pressure

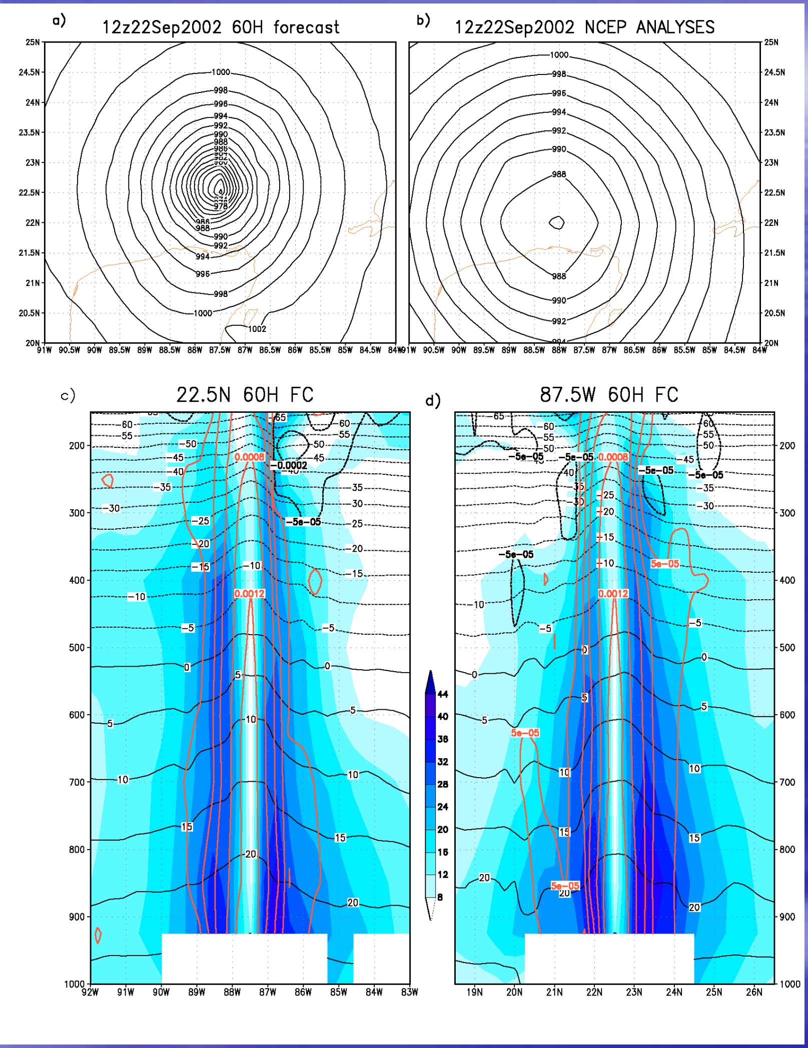
NMC *state-of-the-art* representation of TCs in 1998: no more than 25 m/s, excessively large scale (~1000km); center pressures above 1000 hPa (despite containing Hurricane Hunters flight data). TCs away from operational HH flights were often absent from analyses and forecasts.

Bonnie (1998) cont.



MRF (NMC-now NCEP) state-of-the-art representation of TCs in **1998**: no more than 25 m/s, unrealistically wide eye-like feature (r~100km); very weak warm core

TC Structure: **NASA GEOS-4 in 2004**



Isidore (2002)

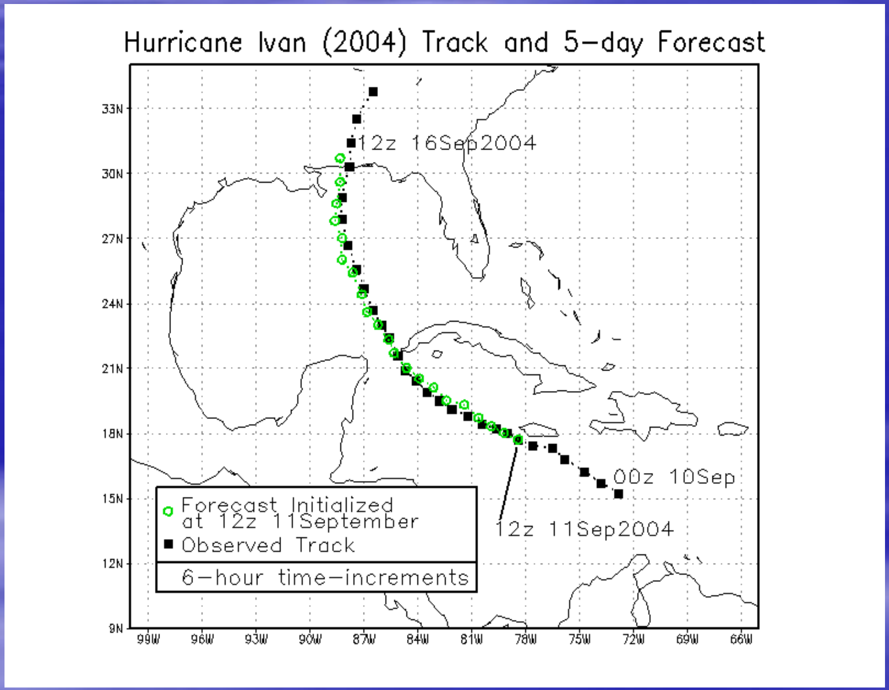
Modeled with GEOS-4 in 2004

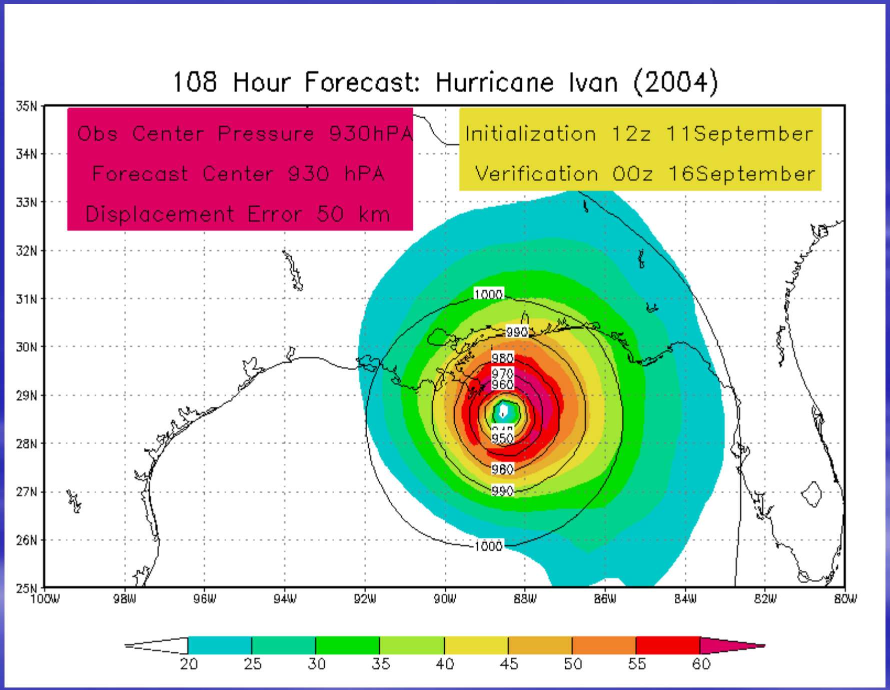
Realistic deepening (center down to 960 hPa, unseen in any un-bogused GCMs). The NCEP Analyses confirm the position but are not as deep with respect to observations.

wind speed,
temp, vort

Atlas, R., O. Reale, B.-W. Shen, S.-J. Lin, J.-D. Chern, W. Putman, T. Lee, K.-S. Yeh, M. Bosilovich, and J. Radakovich, 2005: Hurricane forecasting with the high-resolution NASA finite-volume general circulation model. *Geophysical Research Letters*, 32, L03807, doi:10.1029/2004GL021513.

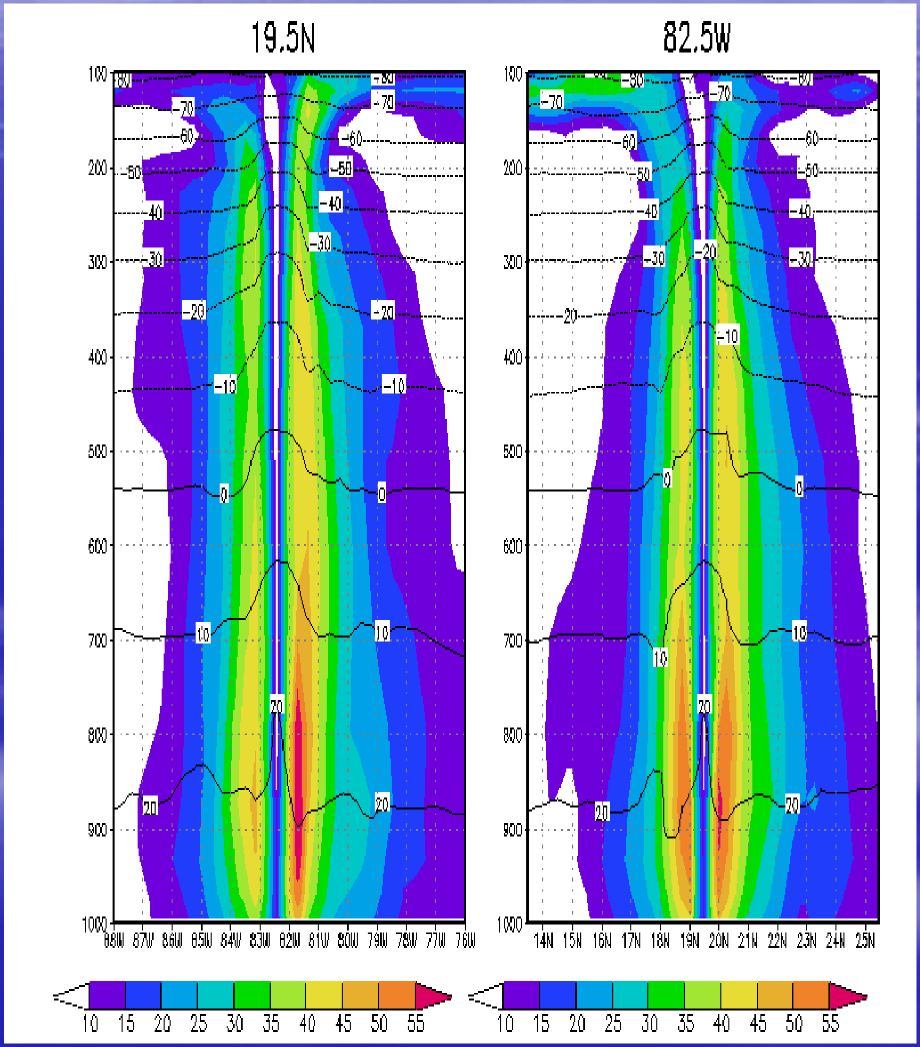
Example of a very realistic NASA GEOS4 simulation in which track and intensity forecast go side-by-side Ivan (2004)





Example of hurricane vertical structure as modeled by the GEOS-4 (2004): Ivan

- The GEOS4 could produce a very compact eye-like feature throughout the troposphere, a prominent warm core; wind maxima located at about 850-900 hPa and a radius of maximum wind of about 50-100 km
- In this 66 hour forecast of hurricane Ivan for 18z12Sep2004, initalized at 00z10September, the 900 hPa wind is higher than 55 m/s

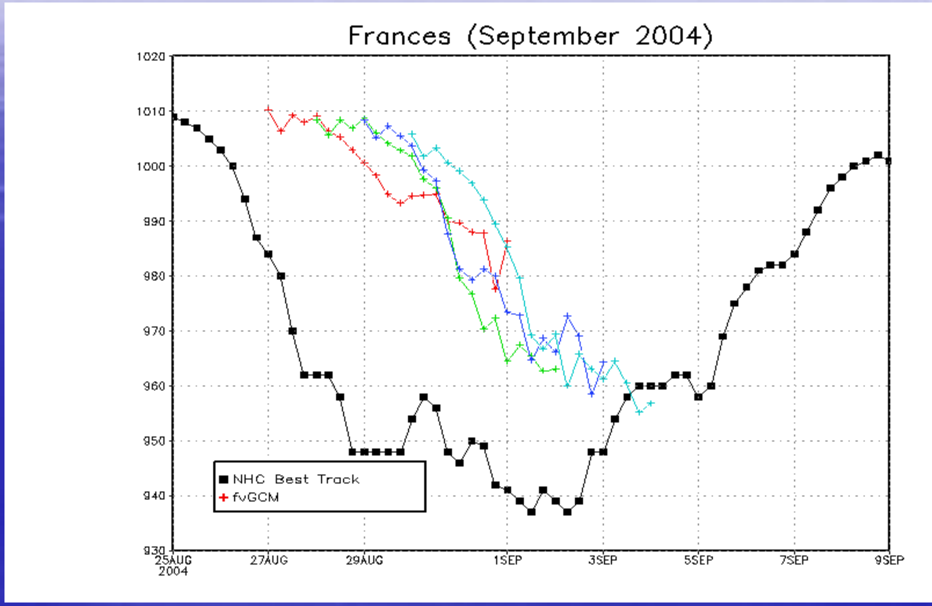


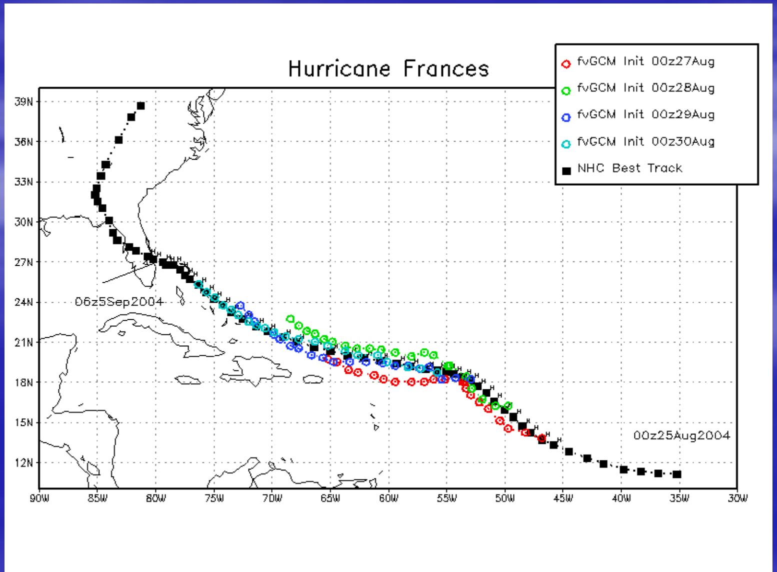
Wind speed, temp

Realistic Cyclogenesis in a global operational model (NASA GEOS-4, 2004) WITHOUT BOGUSING

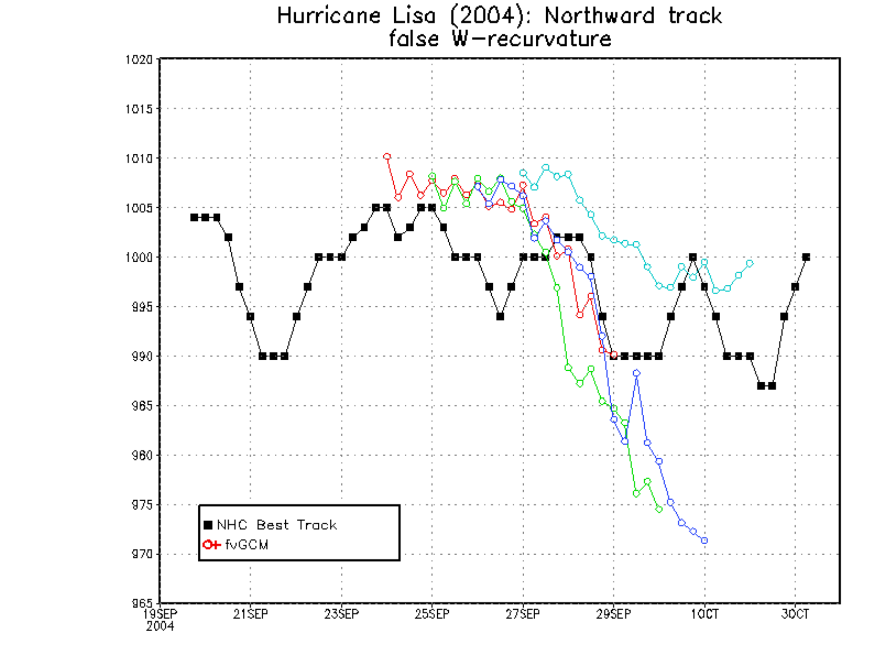
– **Frances (2004): early phase**

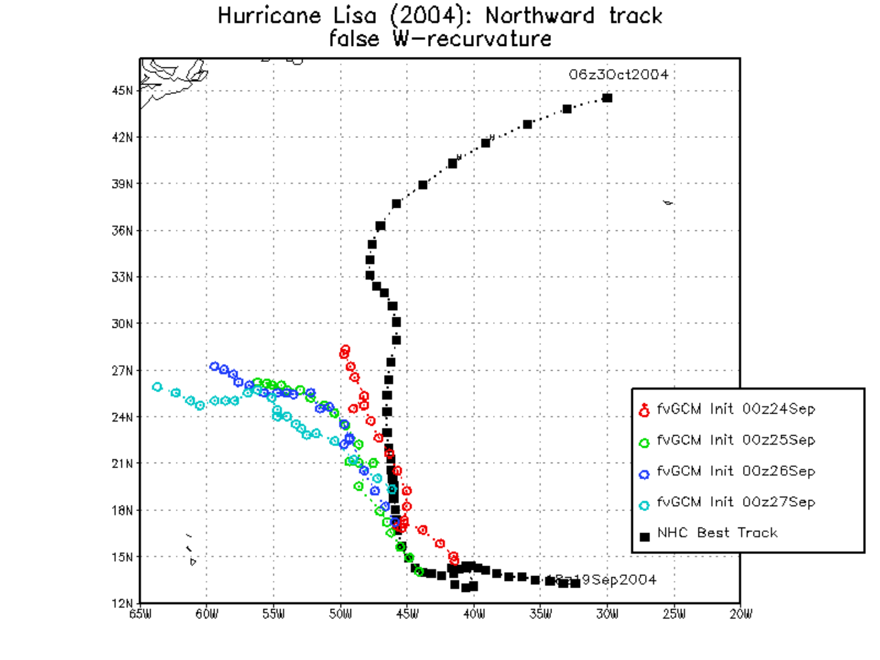
- Example of rapid deepening and good forecast track.
- One run reaches the correct intensity (IC: 00z30Aug) and produces the best forecast track as well





Example of bad GEOS4 forecast sequence due to an incorrect large-scale simulation: (ITCZ displaced of more than 10 degrees, TC over-deepening)





Example of failure in modeling an early recurver (Lisa 2004), in a moderately unfavorable environment and undergoing intensity fluctuations. In some simulations the model overdeepens; in others it does not develop a TC. Track errors are of the order of several ***thousands of km*** and put the model as an outlier with respect to other operational forecast models.

In *forecasting mode*, the importance of the the initializing analyses

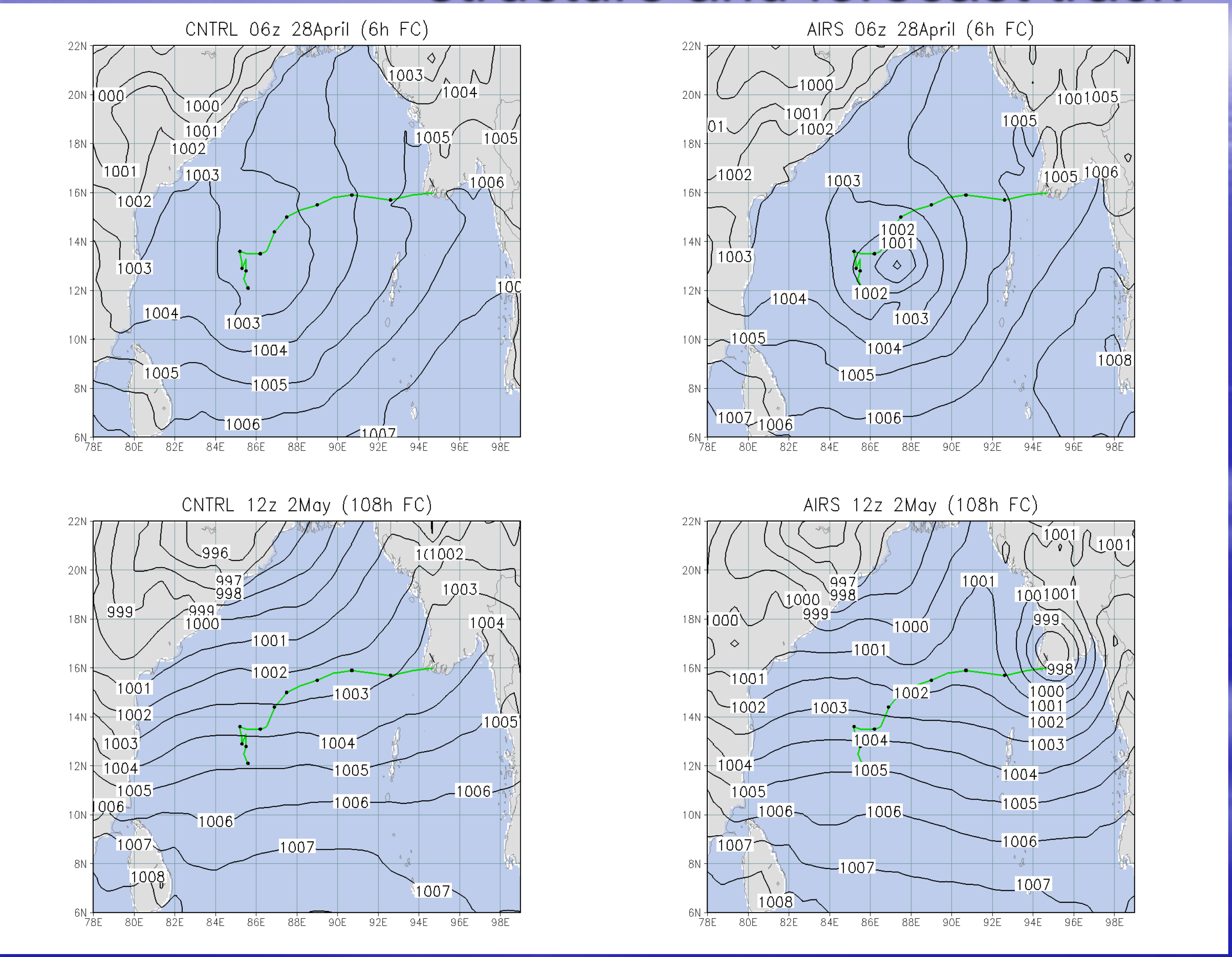
- It is difficult to evaluate the ability of a model performance with respect to TCs
- The overall forecast quality is a blend of the impacts of initial conditions produced by the Data Assimilation System -and- the forecast model capability
- Less-than-optimal model performance with respect to TCS can be somewhat improved with very good initialization.

Collaborative effort aimed at studying the impact of AIRS in the GEOS-5 Data Assimilation and Forecasting System: a *very difficult* tropical cyclone

- Work published in 2009 shows the importance of improving the initialization in the *tropics*. Periods chosen: 15Apr-15May 2009 (boreal spring) to overlap with the catastrophic cyclone Nargis which hit Myanmar causing devastating loss of life
- Tropical Cyclones in the Northern Indian Oceans are more difficult, partly because of short lifespan and erratic tracks. In addition, automated operational global analyses often do not represent these cyclones' position and structure accurately.
- Errors in initial conditions propagate through the forecast and amplify

Reale, O., W. K. Lau, J. Susskind, R. Rosenberg, E. Brin, E. Liu, L.P. Riishojgaard, M. Fuentes, R. Rosenberg, 2009: AIRS impact on the analysis and forecast track of tropical cyclone Nargis in A global data assimilation and forecasting system.
Geophys. Res. Lett., 36, L06812, doi: 10.1029/2008GL037122

Example of analysis improvement leading to better structure and forecast track



Analysis containing AIRS cloudy retrievals
Well-defined Cyclone
Green: Observed Track

AIRS 108-hour Forecast (slp)

Green: Observed Track

CNTRL Analysis (above)
And forecast (below): No Cyclone

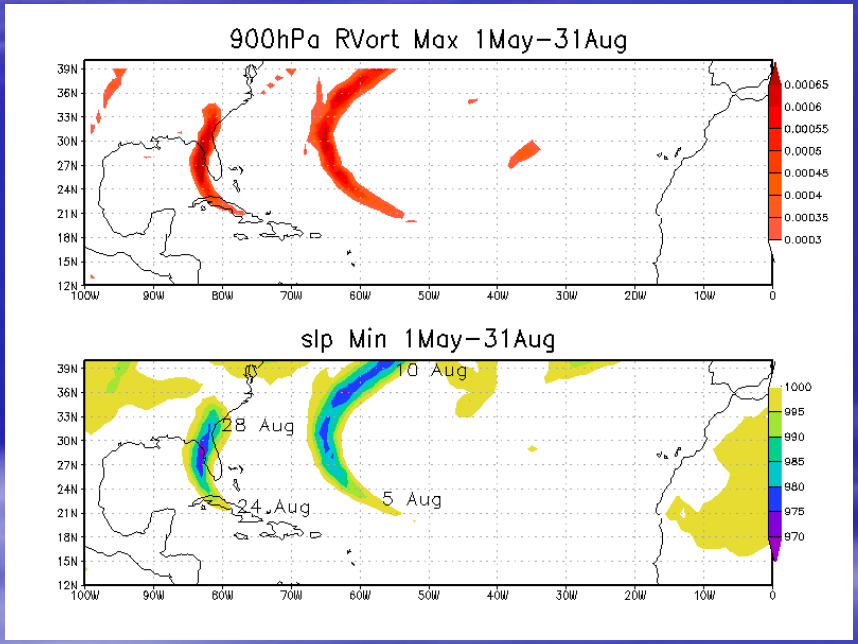
Accurate landfall is produced in the forecasts initialized with AIRS: (Reale et al., 2009, *Geophys. Res. Lett.*)

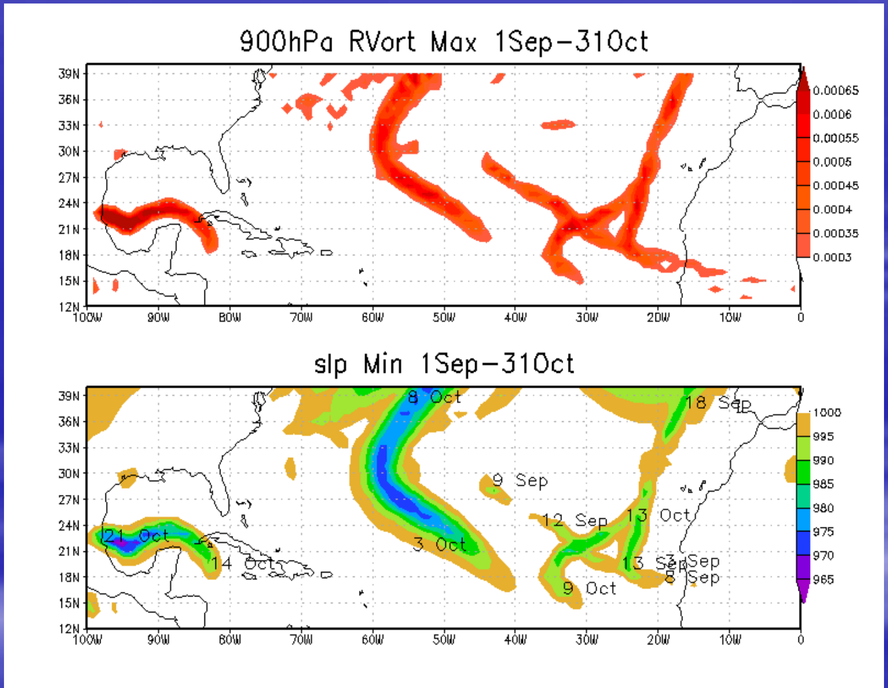
T511 ECMWF Nature Run (2007)

- Free running model – **no memory of initial conditions – no additional data**
- A long simulation is the only way to assess the capability of a forecasting model – as opposed as a DAS+forecasting model. No bogusing, vortex relocation, targeted obs can be added.
- 13-month run, initialized May 2005
- Only SST (2005) and Sea-Ice as boundary forcings
- Analysis published in Reale et al. (2007)

Reale, O., J. Terry, M. Masutani, E. Andersson, L. P. Riishojgaard, J. C. Jusem, 2007: Preliminary evaluation of the European Centre for Medium-Range Weather Forecasts (ECMWF) Nature Run over the Tropical Atlantic and African Monsoon region. Geophysical Research Letters,} 34, L22810, doi:10.1029/2007GL31640.

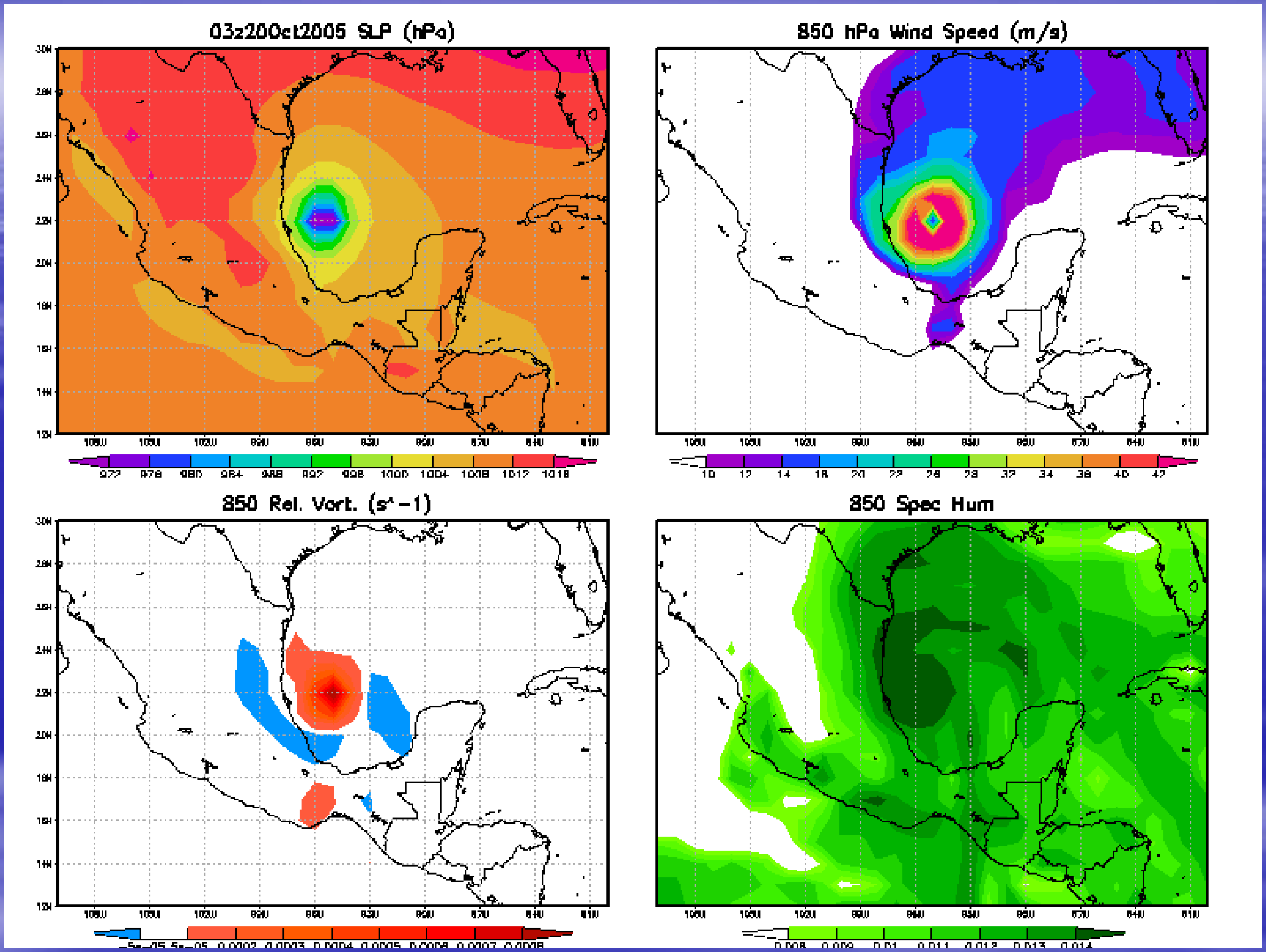
EC T511: very realistic activity
At least 9 strong systems





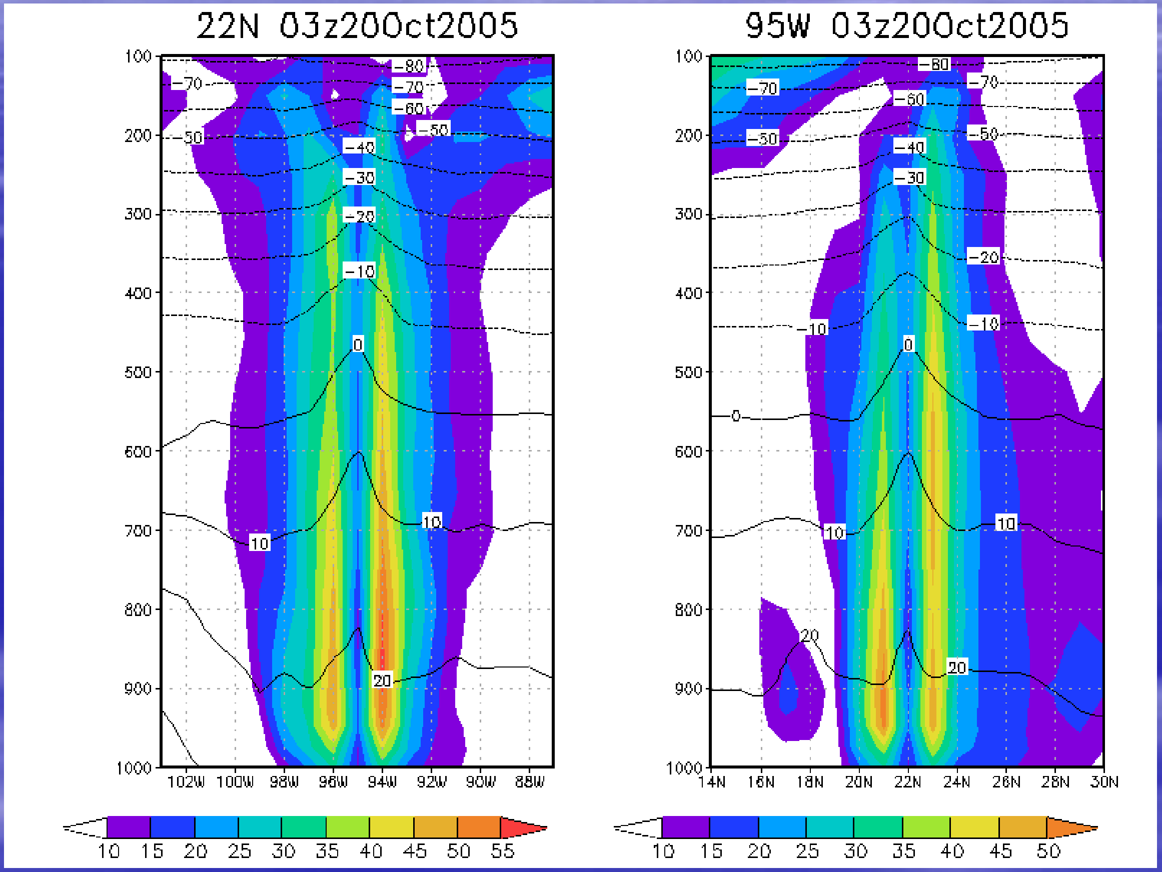
Only TCLs having a center pressure of less than 1000 hPa in the 1x1 fields and 900 hPa vorticity greater than 3×10^{-4} s^{-1} are considered

EC T511: Horizontal structure of a Hurricane



Pressure center and 850hPa wind are very realistic (970 hPa and 50 m/s)

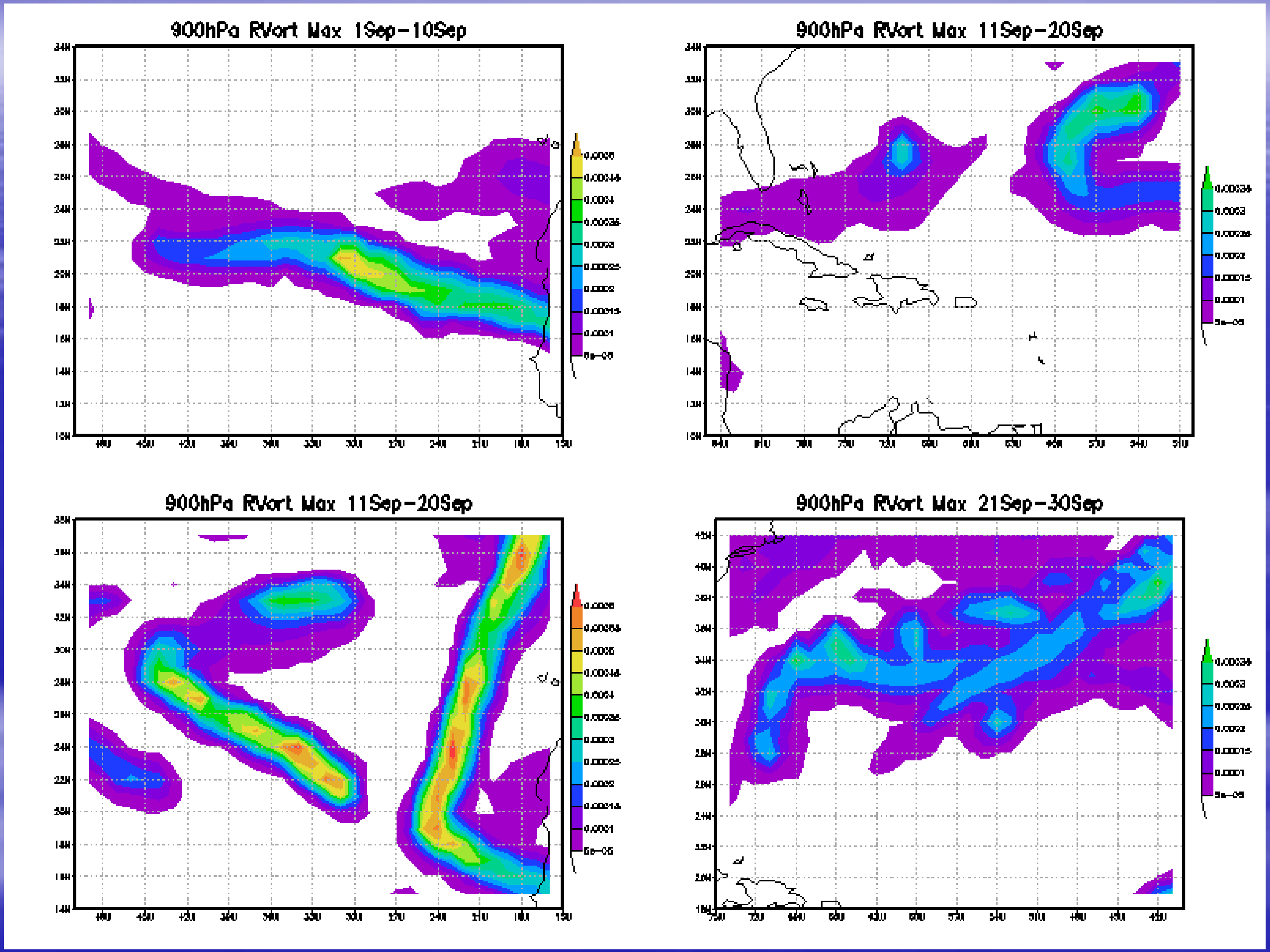
EC T511: same hurricane - vertical structure



Wind speed (m/s)
Temp (^oC)

Vertical structure of a HL vortex showsa distinct eye-like feature and a very prominent warm core. Low-level wind speed exceeds 55 m/s

EC T511: Realistic Variability of Atl. TC tracks



Looping and Binary vortex interaction

4 systems:
Looping,
Binary vortex Interaction,
Extratropical Transitions
and Extra-tropical Re-intensification

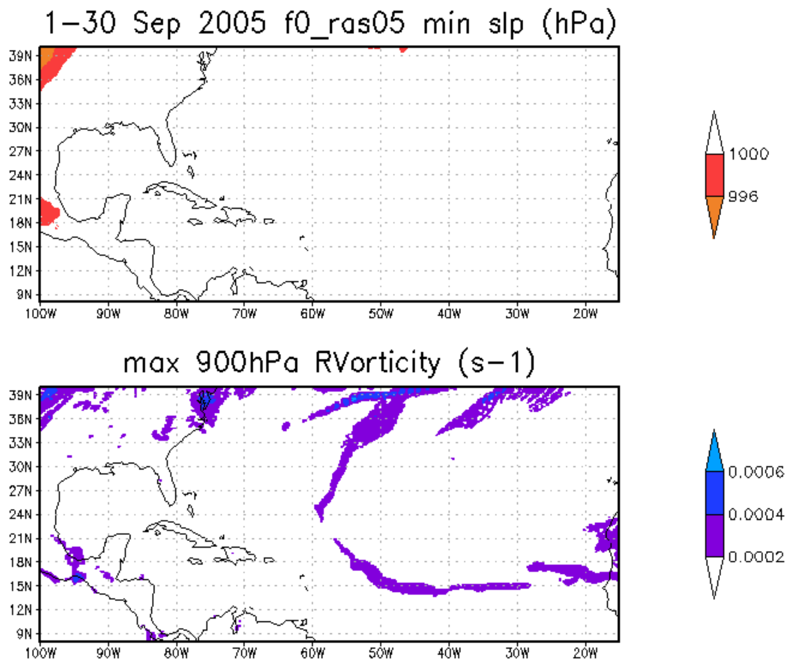
Singuarities, binary vortex
Interactions, Intensity fluctuations
Due to large-scale forcing fluctuations

A long simulation must produce complex tracks

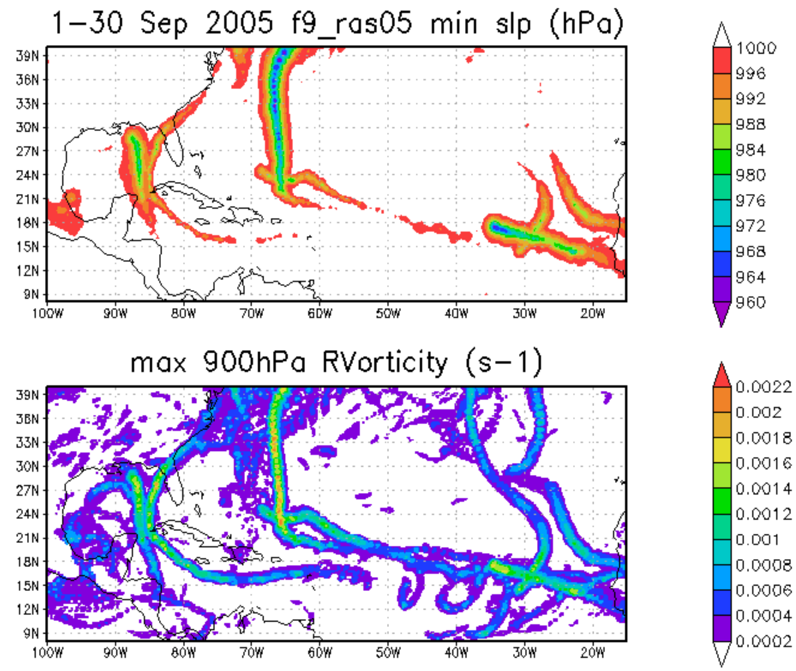
GEOS-5 with Tokioka (2009): Same experiment settings of NR ECMWF

Behavior comparable to the EC T511

Control Run GEOS-5 0.25 (with rel. Arakawa-Schubert)



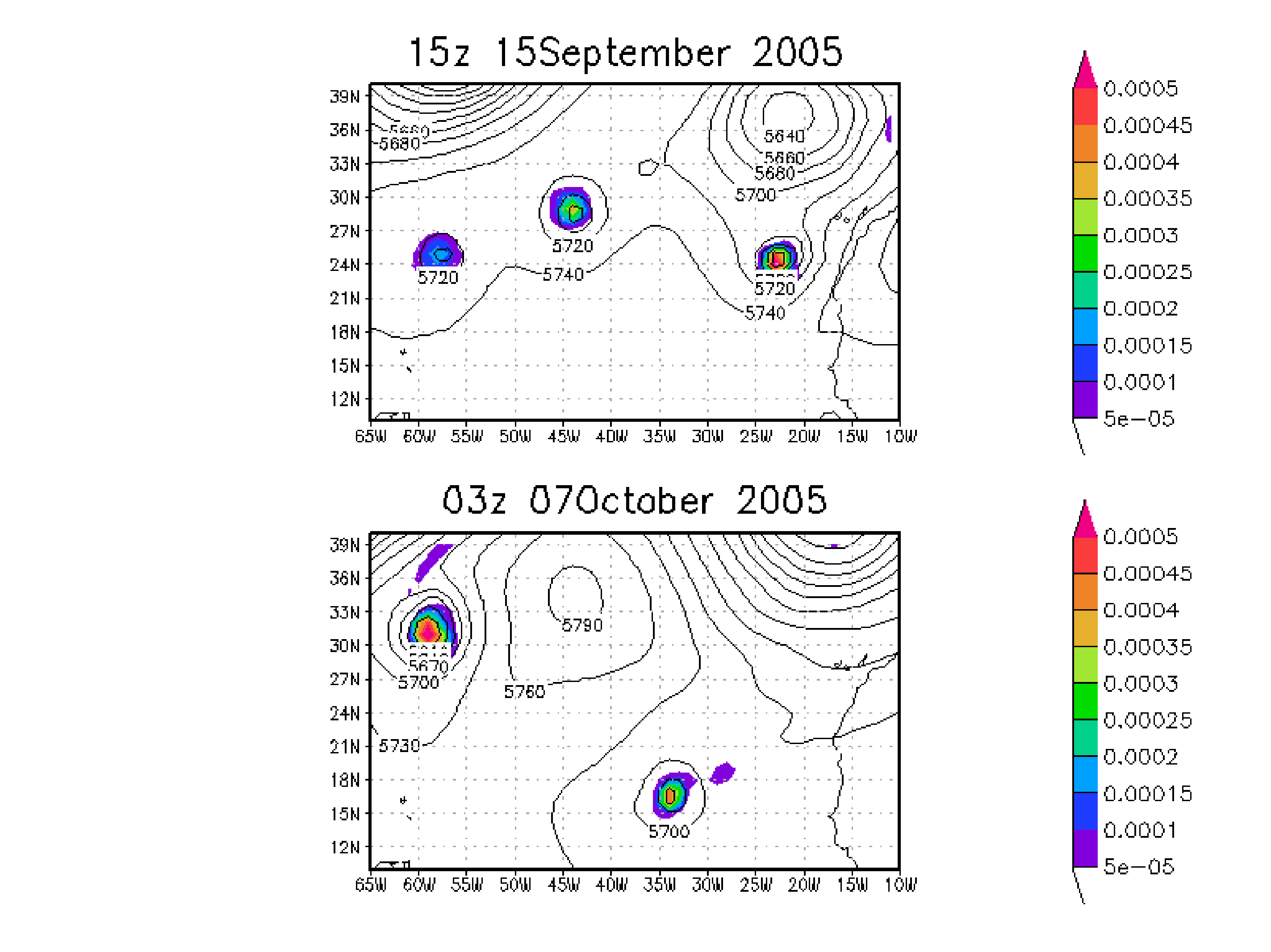
GEOS-5 (with Tokioka)



No cyclone reaches 1000hPa in the Control during September.
At least 7 cyclones below 1000 hPa in the GEOS-5 w.Tok. One hurricane goes below 960hPa. Very realistic track variability, scale.
Even non-developing waves are well captured.

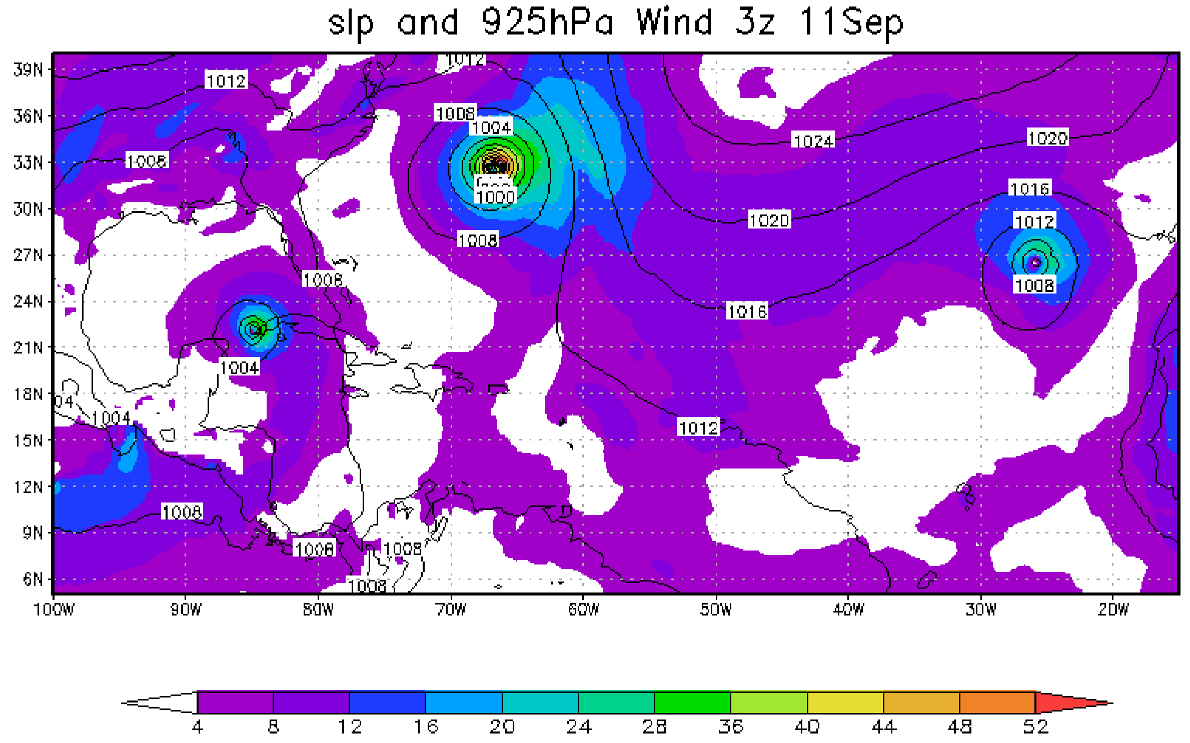
EC T511: Multiple simultaneous tropical cyclones can be present in the Atlantic in very active seasons

Another important –realistic- capability of the ECMWF NR



500 hPa geop (m) and 900 hPa rel vort (s^{-1})

3 TCs simultaneously present in the GEOS-5 w. Tokioka 11Sep



Slp (hPa) and 925 hPa wind (m/s)

Proposed Work on TCs in high resolution climate simulations

- We will compare the structure of cyclones in a resolution-independent matter
- to assess the degree of `efficiency' that a model has in representing a
- tropical cyclone at a given resolution.
- We propose some diagnostics to assess the quality of a representation of a mature tropical cyclone.   Some of the investigated issues are:

Proposed Work (cont.)

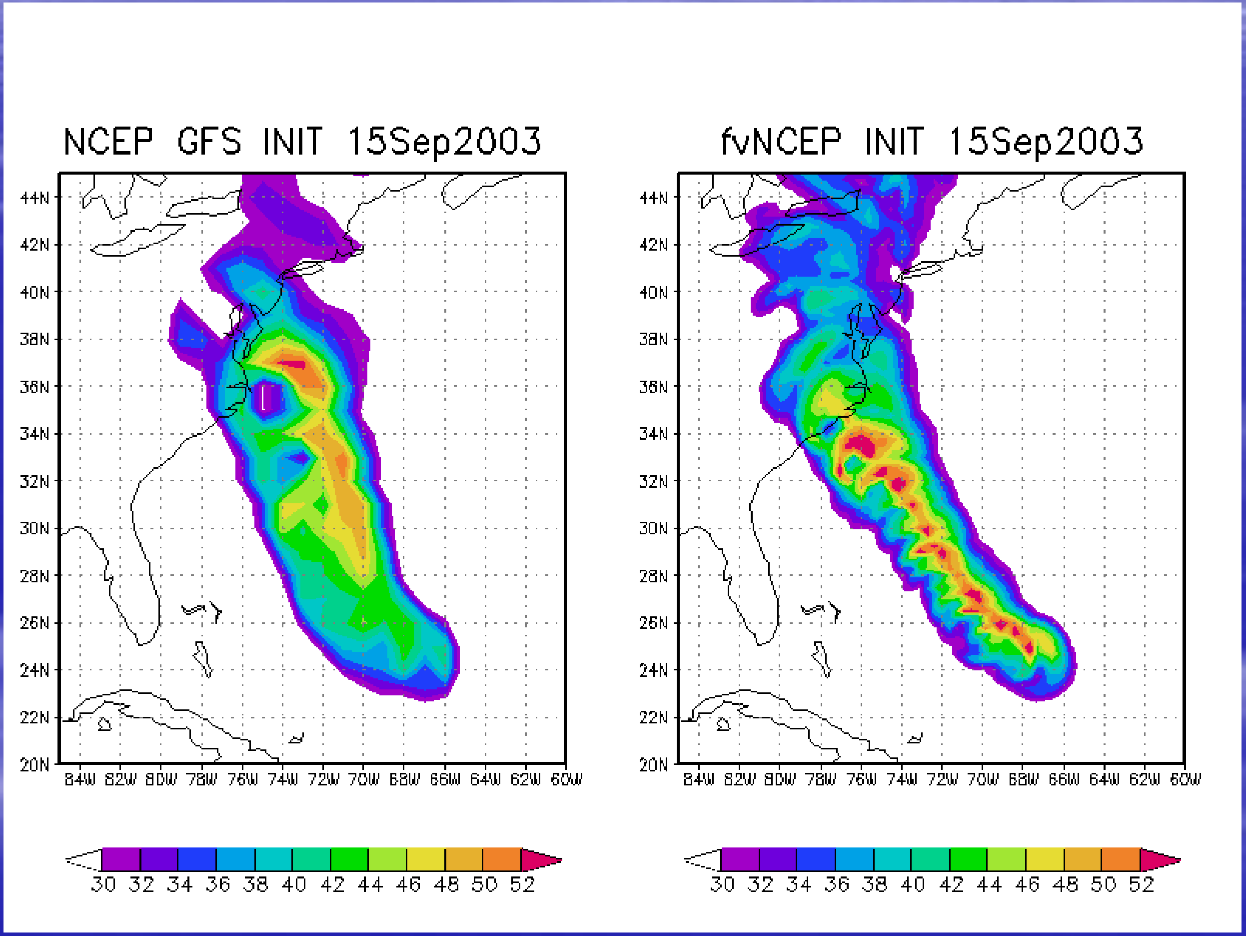
- Intensity
- Vertical Structure
- Warm Core
- Horizontal Compactness
- Tropical cyclogenesis:
- Extra-Tropical transitions

Work in progress, future work

Intensity

- In the operational forecasting environment, 10m observed wind and center pressure are currently used
- PROBLEM: excessively high drag in the marine boundary layer seems to occur in global models when winds exceed 30m/s: 10m wind often about 60% of the 850hPa wind (unlike 90% in real world)
- Possibly due to unrealistically high roughness length over oceans with wind speeds exceeding 30m/s
- As a consequence, it may better to use 850hPa wind as intensity diagnostics in global models
- One simple way of assessing comprehensively the TC intensity reached in a simulation is to produce the max wind at 850hPa throughout the system’s lifespan

Example of Intensity inferred from 850hPa wind max (Isabel, 2003)



Operational GFS and GEOS-4 have comparable intensity
Different degree of compactness

Warm Core Structure

1) One immediate, effective way of assessing if a model produces a vertically aligned and symmetric system, is to measure the *strenght of its warm core*. One simple way is simply to subtract a standardized zonal mean intersecting the center of the storm. Examples: GEOS-5 versus NCEP GFS

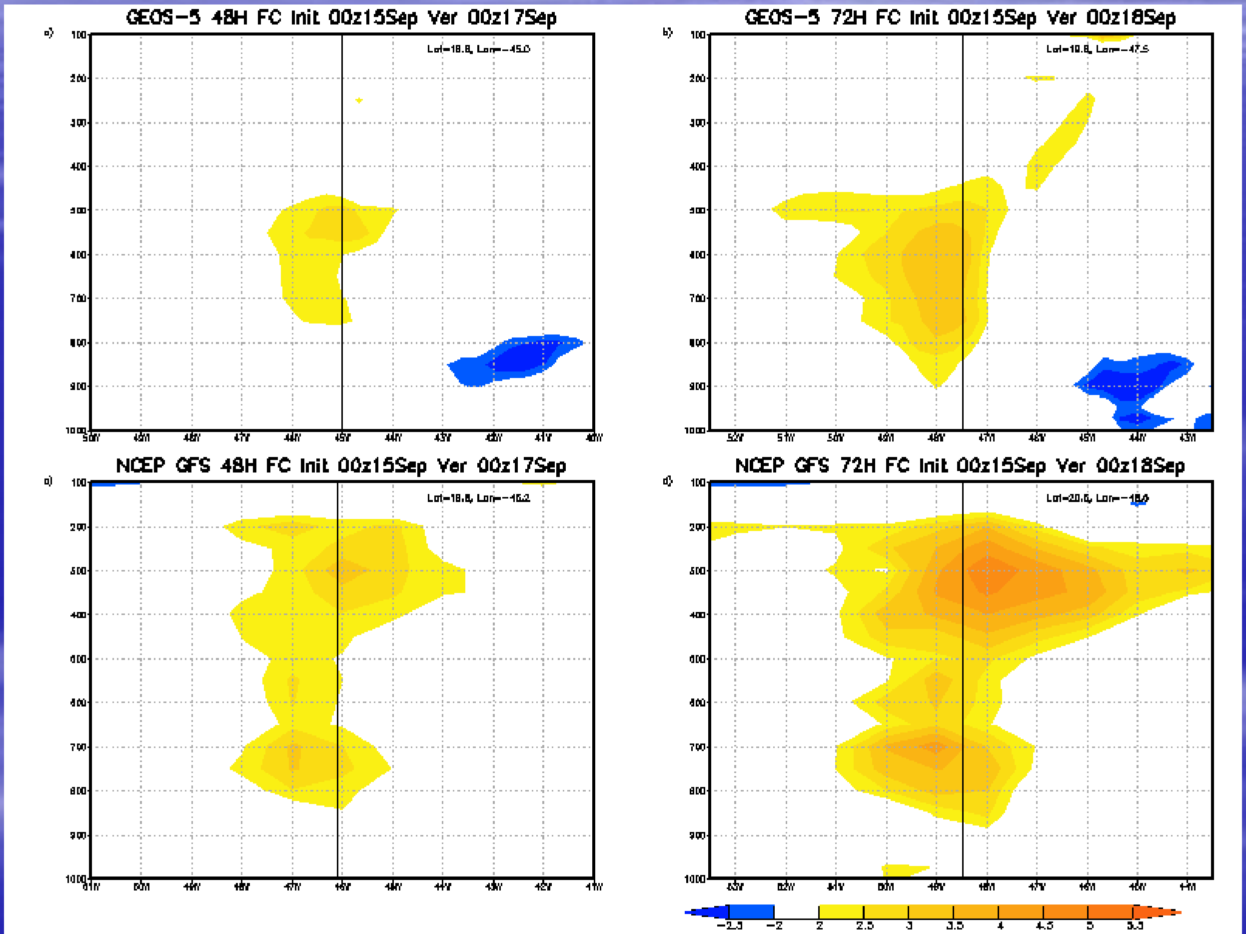
Examples of warm core (Helene, 2006)

48-h Fc

72-h Fc

GEOS-5 (0.25)

GEOS-5 (0.25)



GFS

GFS

48-h Fc

72-h Fc

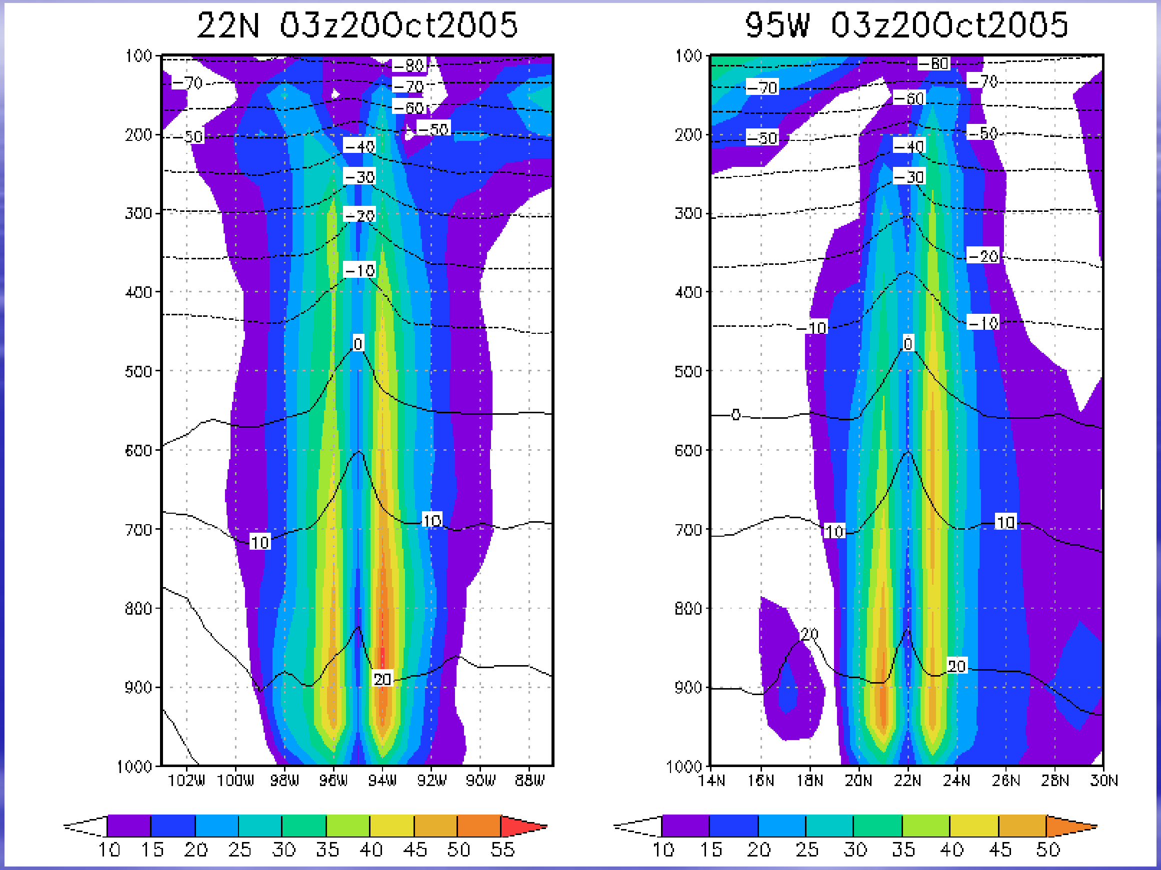
Ms. M. Fuentes, Ph.D. Thesis

Vertical Structure inferred through zonal and meridional vertical cross-sections of wind speed and temperature of mature TCs in the deep tropics

Desirable features:

- Wind maximum at 900hPa or lower
- Small adius of maximum wind
- Perfectly vertically aligned low-speed column
- Vorticity column with maximum in the lower levels
- Low-level convergence confined below 800 hPa
- Upper-level divergence confined above 200 hPa

EC T511 NR: strongest hurricane - vertical structure



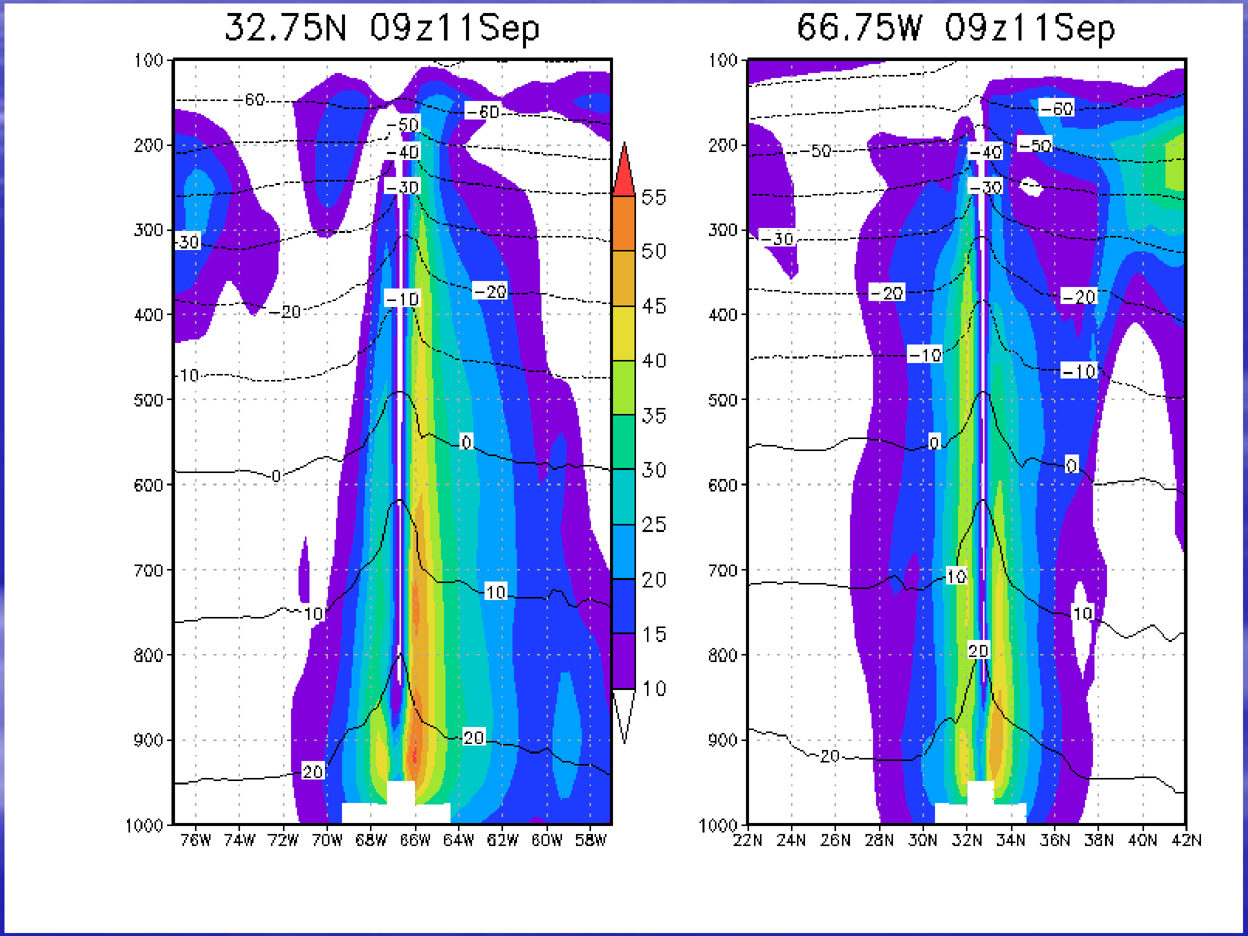
Wind speed (m/s)
Temp (°C)

Zonal

Meridional

Vertical structure of a HL vortex shows
a distinct eye-like feature and a very prominent warm core.
Low-level wind speed exceeds 55 m/s

Strongest Hurricane in GEOS-5 w.Tokioka



Zonal

Meridional

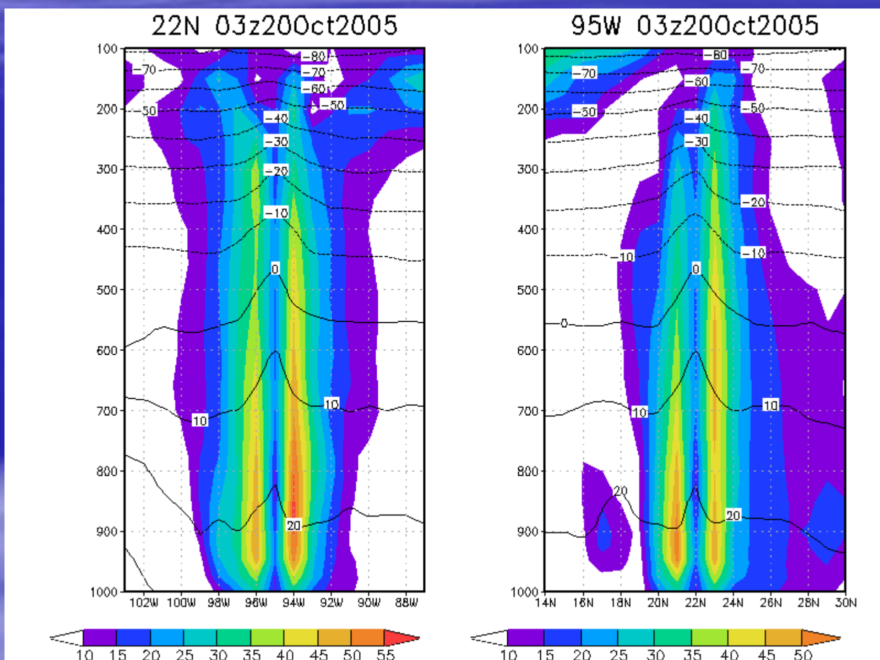
Wind up to 60 m/s

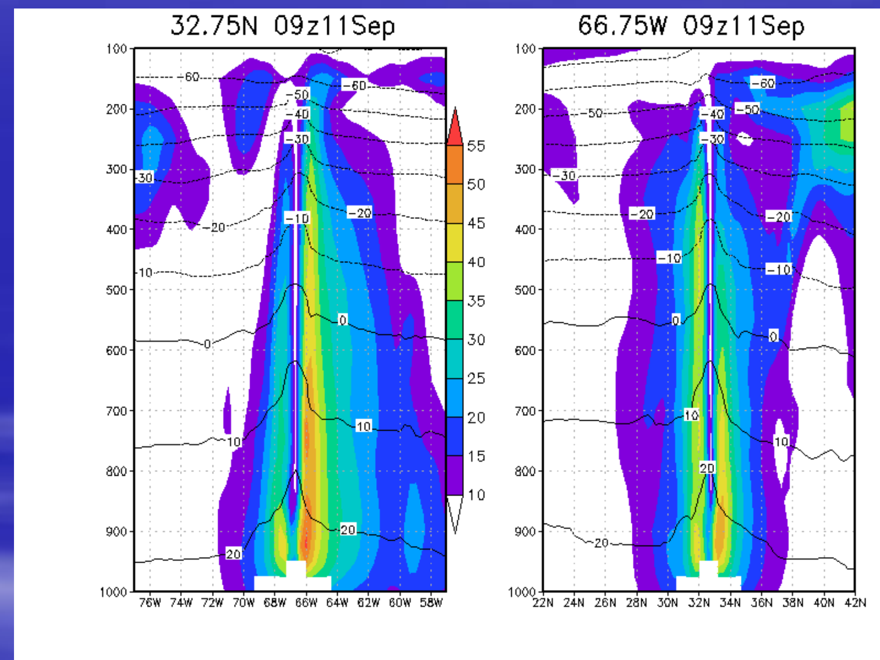
Wind max at less Than 900hP

Well-defined warm core

Very realistic scale

Side by side comparison with ECT511:





EC T511 (2007)

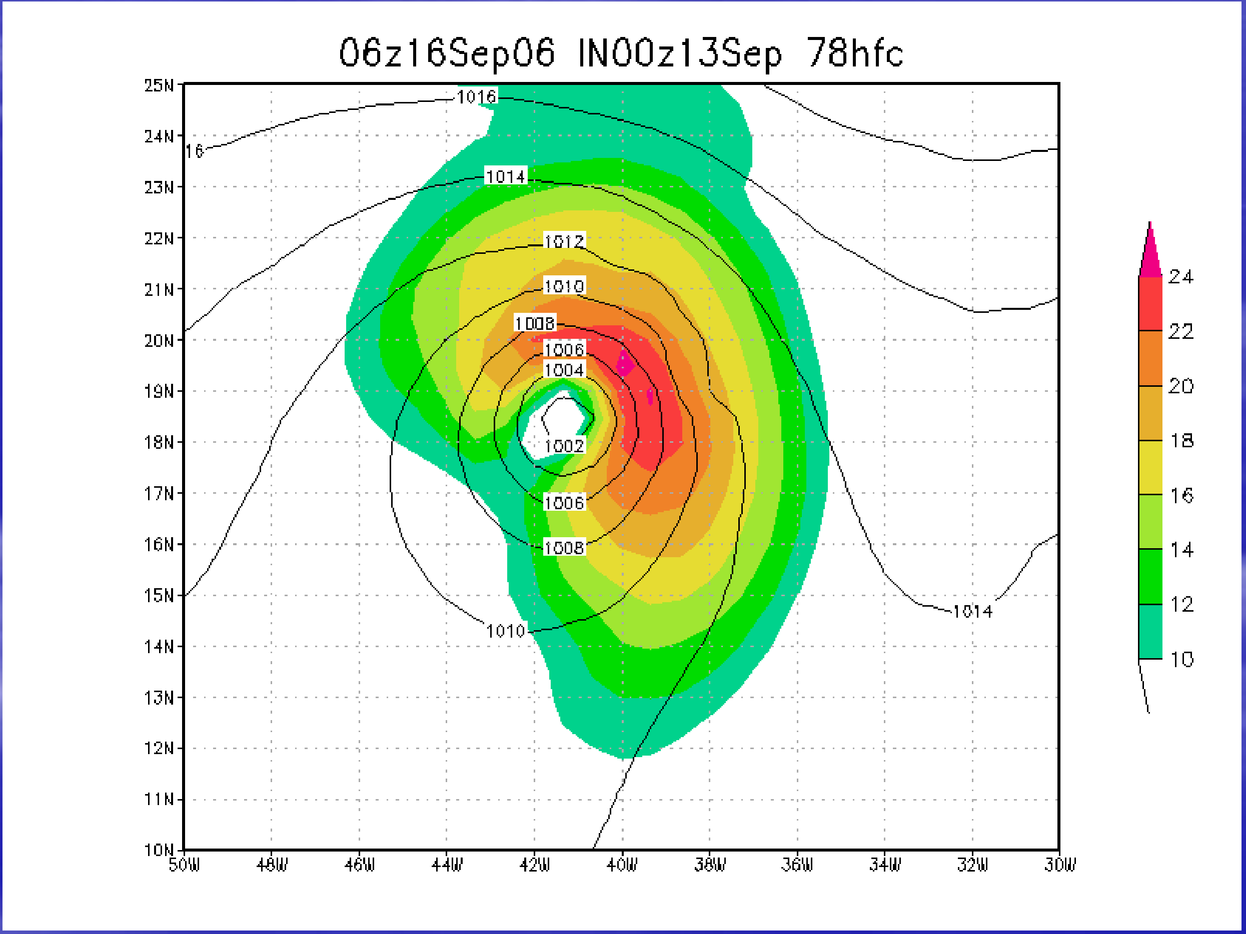
GEOS-5 with Tokioka (2009)

GEOS-5 has slightly sharper warm core, better-defined eye, max wind at lower elevation, slightly smaller radius of max wind. Intensity is about the same.

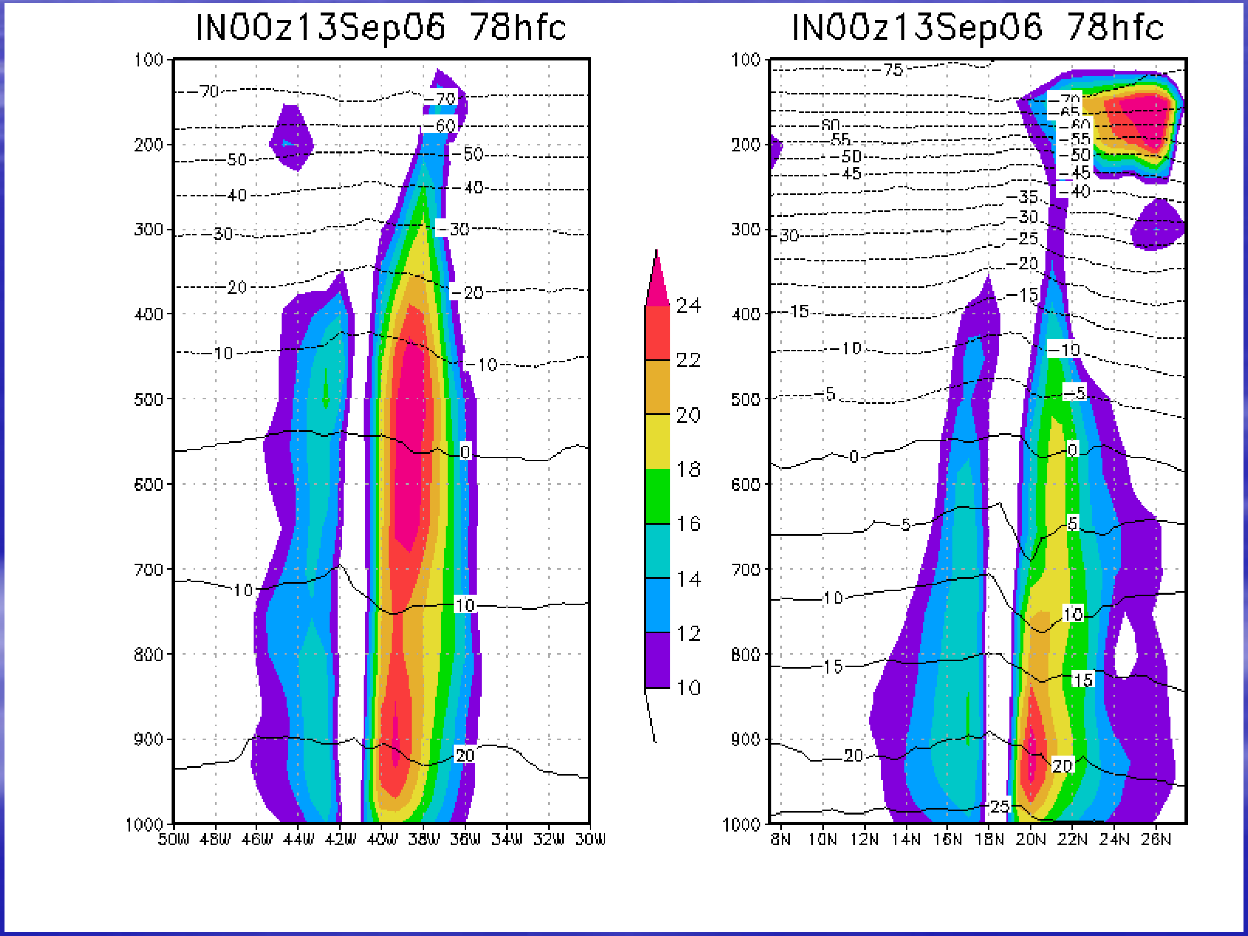
Horizontal scale

Horizontal Compactness, ratio of radius of maximum wind (rmw) over radius of wind greater than the environmental wind of a given threshold, which we can consider the radius of the tropical cyclone (TC) in the model (rtc). The wind magnitude of a modeled tropical cyclone decreases from the center and is not distinguishable from the large-scale wind at a certain distance. This distance could be considered the tc-influenced domain in the model and can be compared with the rmw. The smaller rmw with respect to the rtc the more realistic the modeled cyclone is. In low resolution global models, the radius of maximum wind occupies a large fraction of the domain affected by the cyclone.

Example from GEOS-5 v.2:
how **compact** is this 0.5 simulation of Helene?



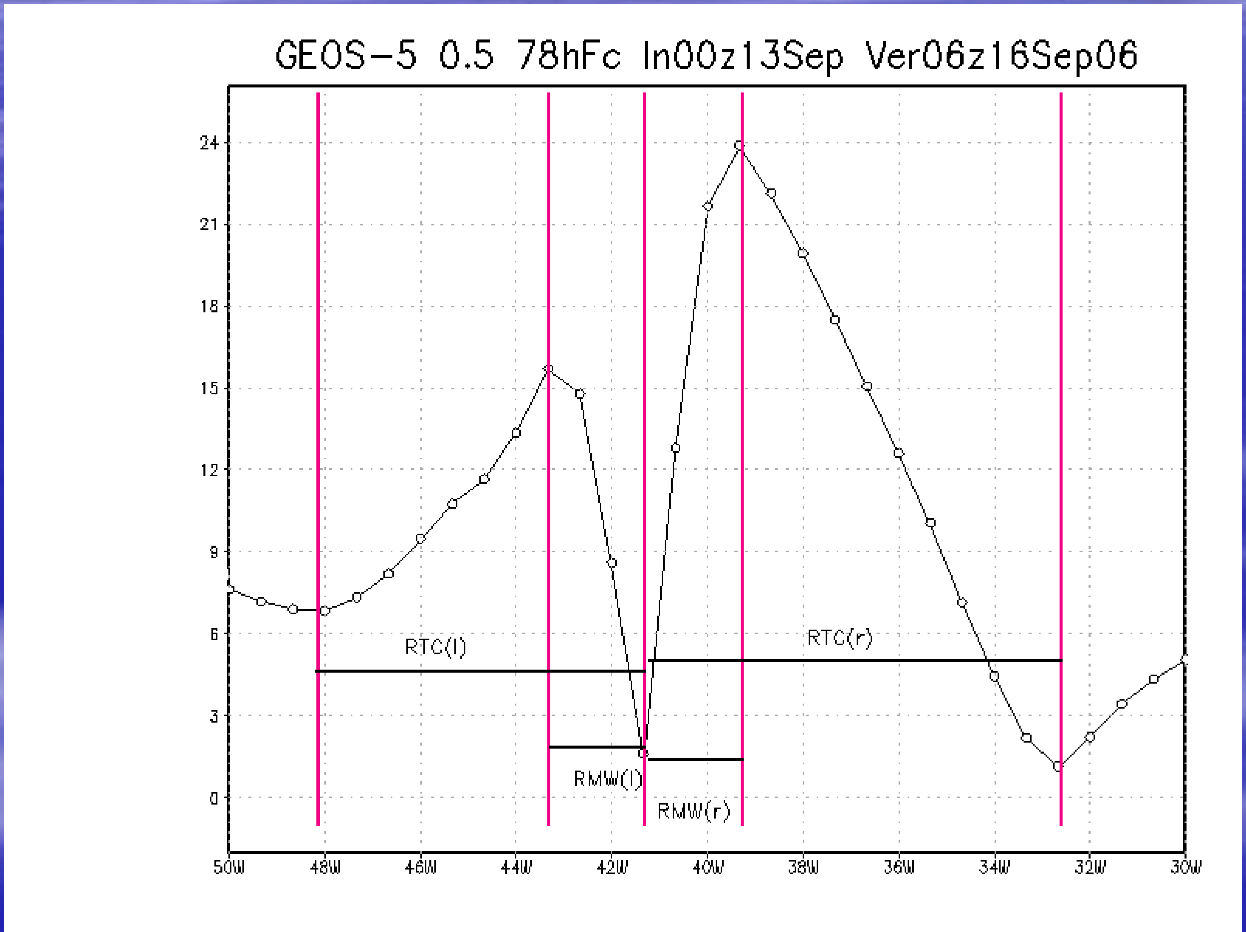
Vertical structure tells that **Helene (2006) as produced by the GEOS-5 v.2 (w RAS) was not a very good simulation**



NOT a very good representation:
lack of warm core
Sloping isotherms
Across the eye
Max winds at 500 hPa

18.5 N 06z16Sep2006 41W

Compactness evaluated in GEOS-5 simulation at .5 for **Helene (2006)**

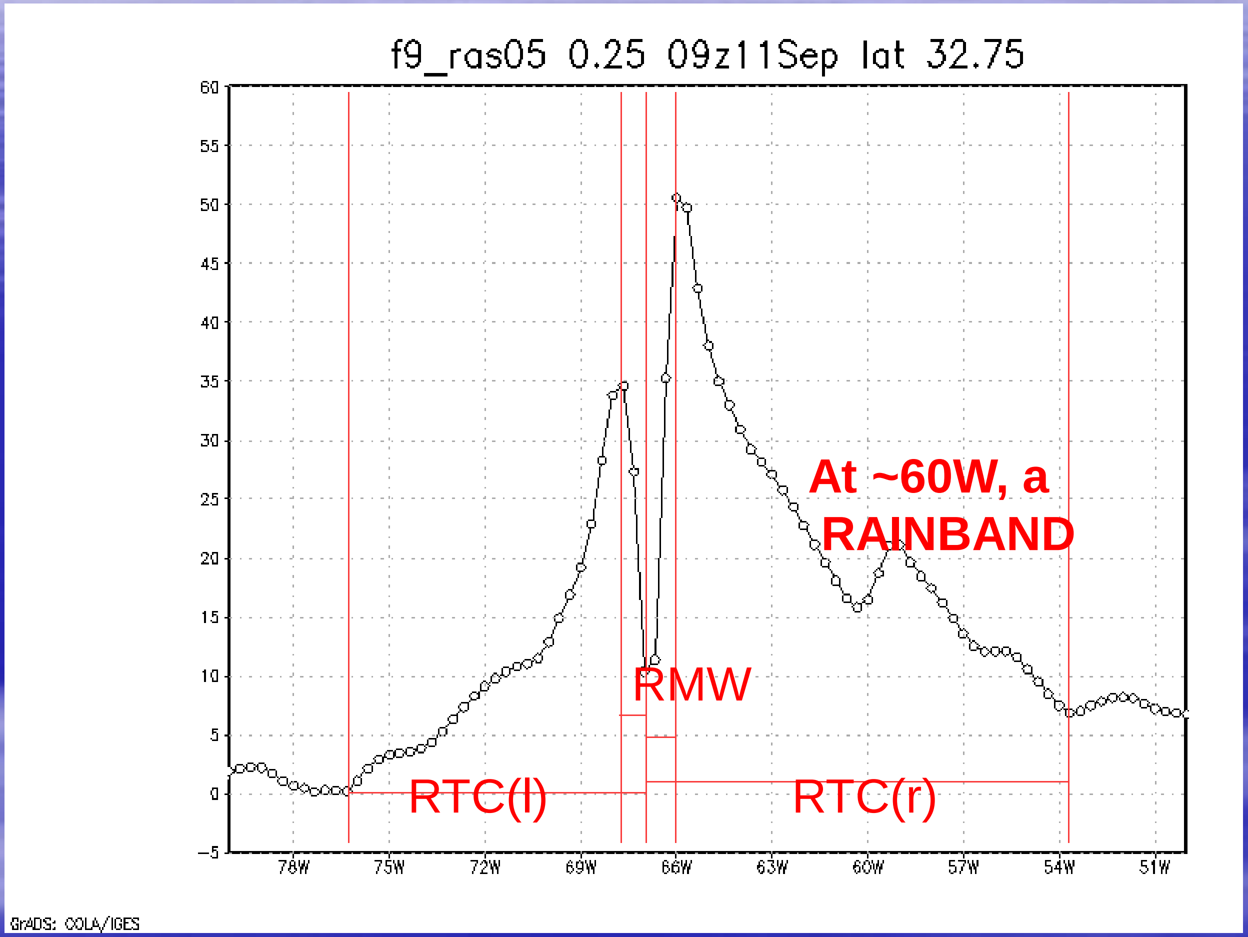


850 hPa wind at 18.5N

Despite being a relatively weak simulation,
the representation of the system is quite compact in the above sense

[RMW(l)+RMW(r)] / [RTC(l)+RTC(r)]=**0.27**

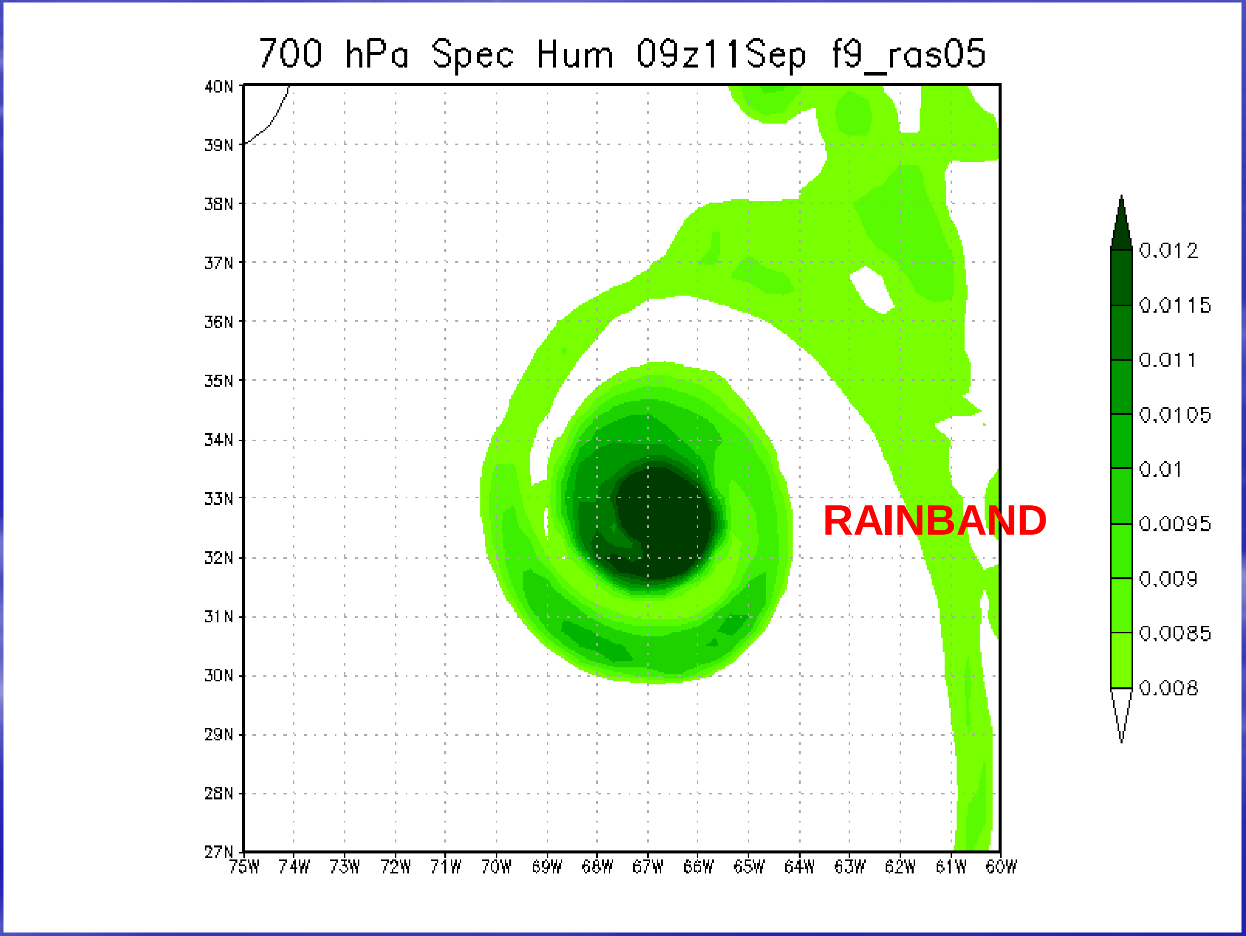
Compactness in the GEOS-5 w. Tokioka at 0.25



[RMW(l)+RMW(r)] / [RTC(l)+RTC(r)]=0.07-0.10

If we include or not the `rainband' in RTC(r)

Very clear evidence of a rainband at 61W



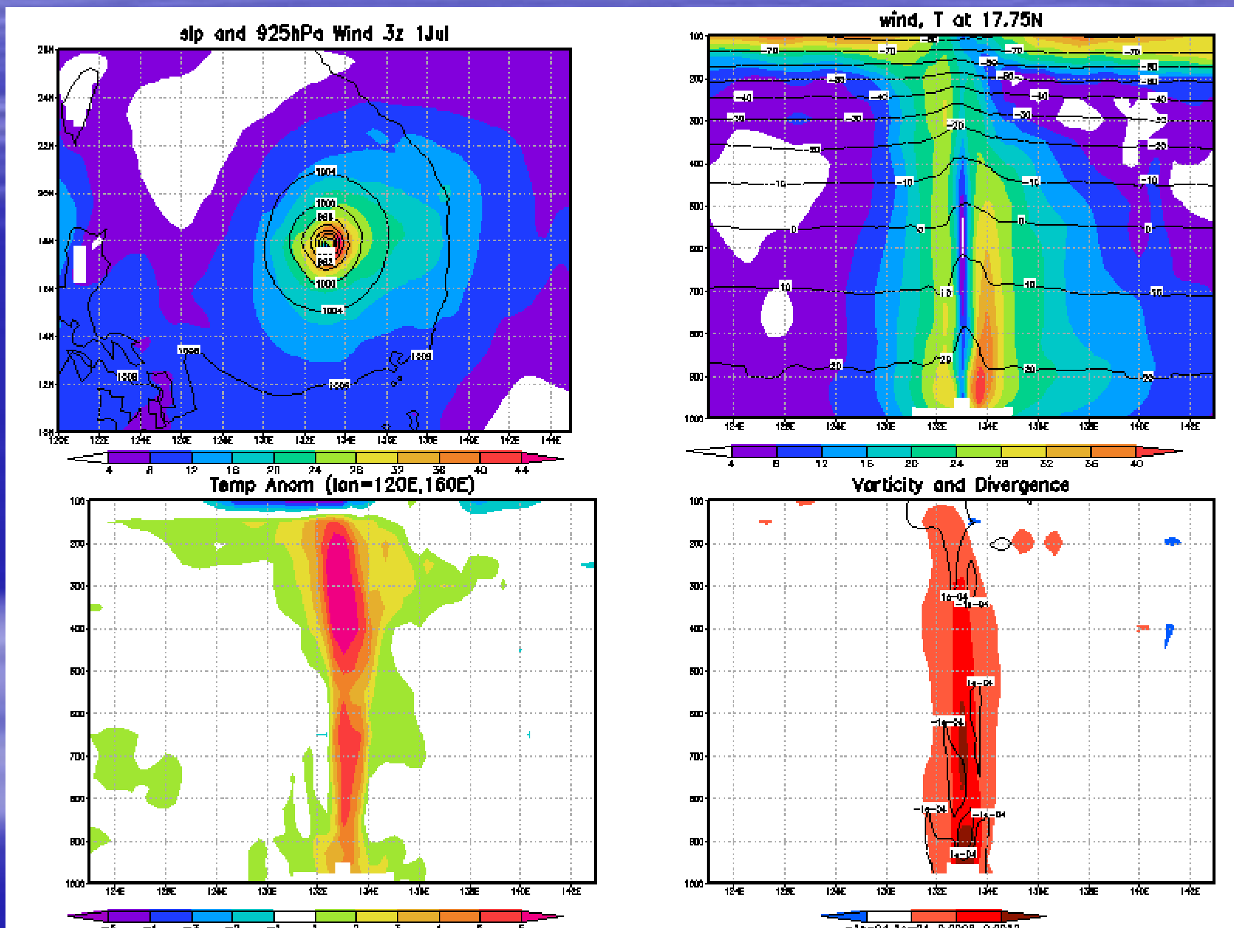
Examples of Horizontal Compactness (HC) evaluated from a limited sample

- ECMWF NR T511; HCN=0.15-0.25
- GEOS-5 0.5; HCN=0.20-0.40
- GEOS-5 0.25; HCN=0.15-0.35
- Perfect hurricane (obs.) = 0.05-0.15
- *GEOS-5 w.Tokioka = 0.07-0.2*

Cumulative diagnostics for the same system

- To provide representations of vertical and horizontal structure of the same system in one plot is a convenient way to immediately compare models
- Vertical sections of wind and temperature; vorticity and divergence; warm-core anomaly
- Map of slp and 850 wind

Typhoon in July (GEOS-5 w Tok.)

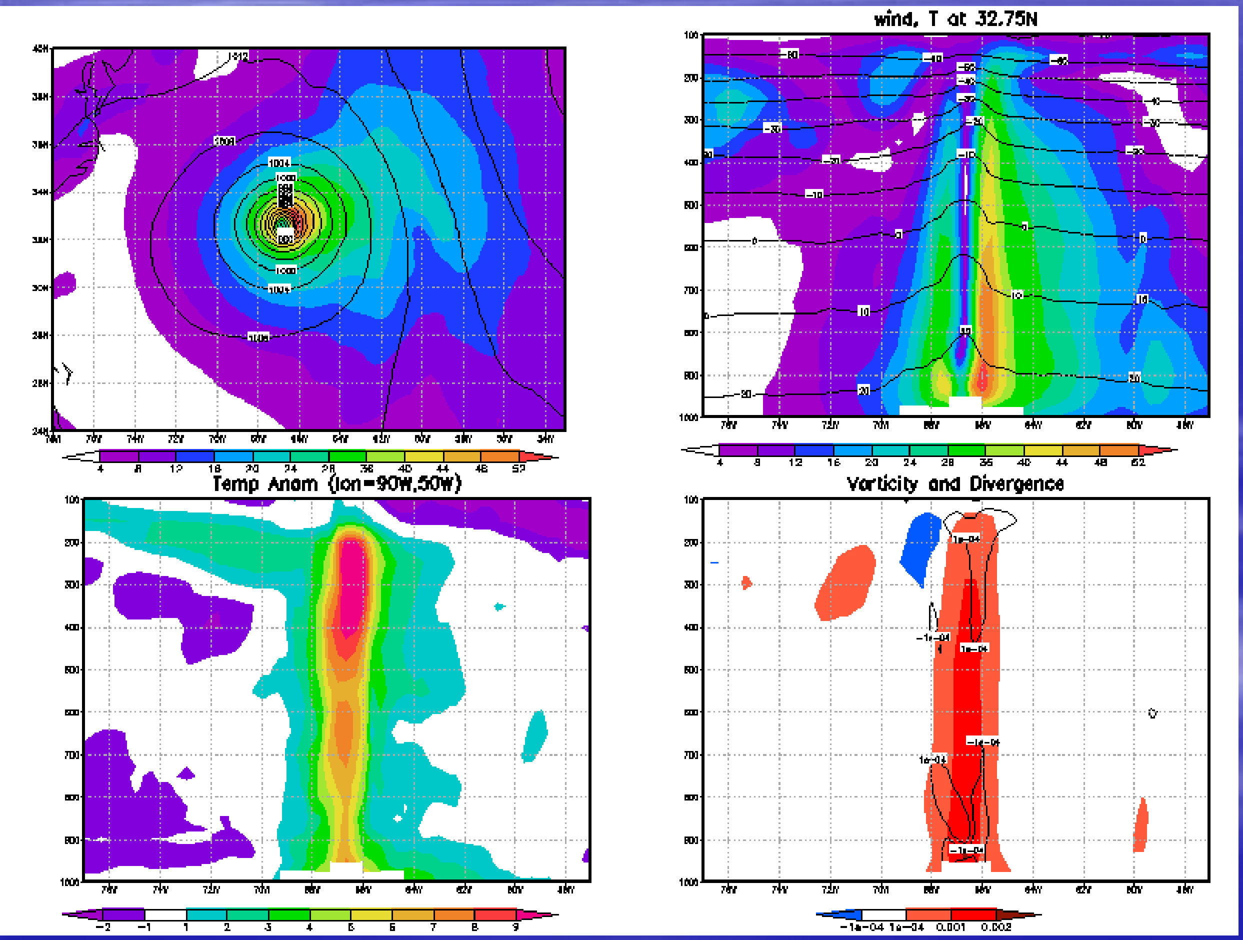


Winds above 40m/s

Vorticity above 10-3s-1

Warm core up to 6C

Hurricane in the Atlantic
(GEOS-5 w. Tok)



Winds up to 60m/s

Vorticity up to 3x10-3s-1

Warm core up to 10C!

Ongoing work: Vertical structure

We propose to assess vertical compactness, as ratio of the thickness of the outflow over the thickness of the nondivergent flow.
From a fixed-size area around the storm we produce area-averaged vertical divergence profiles.
Different profiles can be compared and the ratios the thickness of the outflow over the nondivergent flow (which is a nondimensional quantity) is a measure of the quality of the representation, since the outflow in nature is confined to a relatively shallow layer between 200 and 100 hPa, whereas in global models it affects almost all levels above the midtroposphere. Horizontal resolution does affect the confinement of the outflow also in the vertical, not just the horizontal-scale compactness.

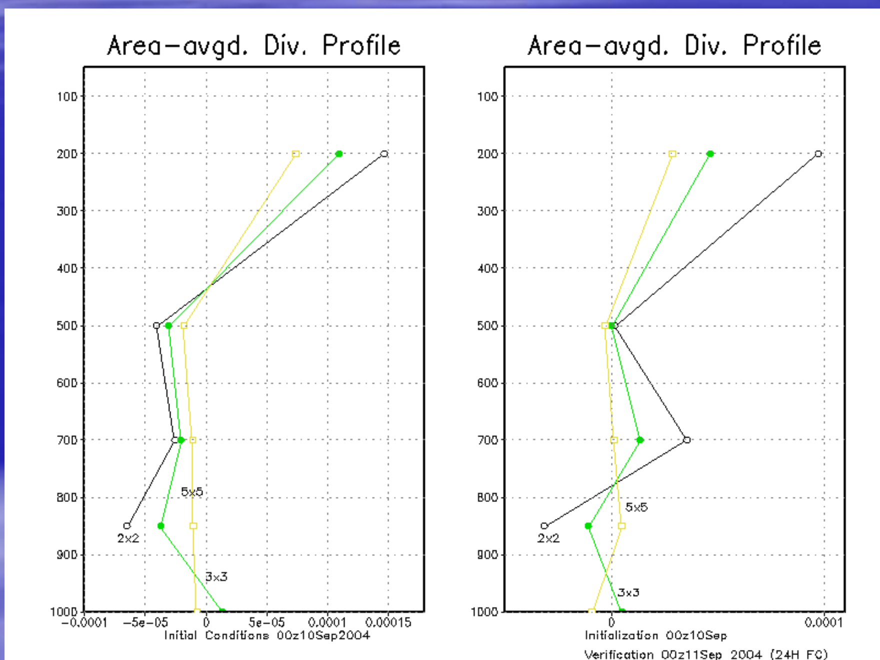
Examples: vertical structure change in a 24-hr fc The `ideal' divergence profile structure was not reached in 2004

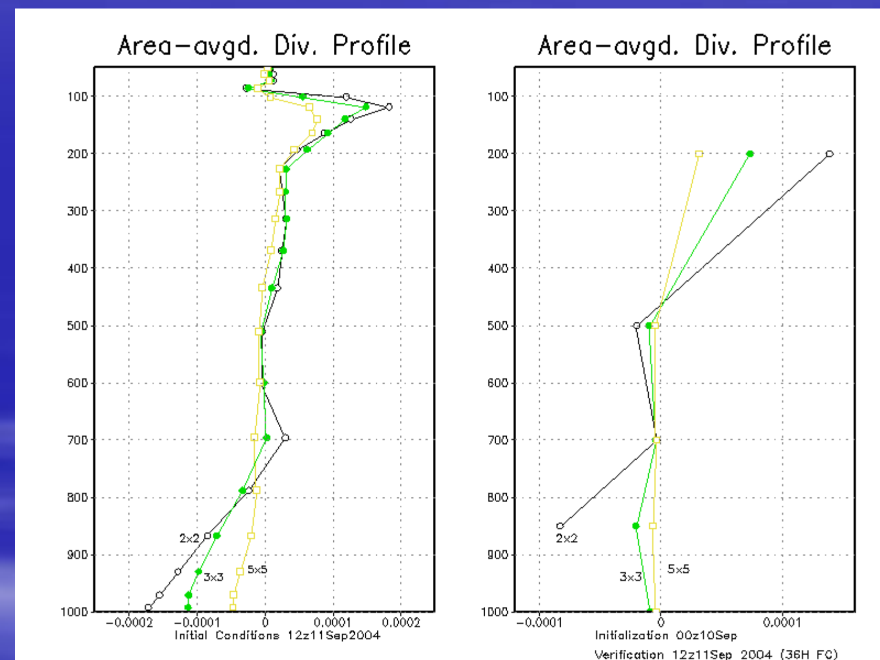
Divergence profiles averaged on 1x1, 2x2, 5x5 deg boxes (Ivan, 2004)

NCEP

GEOS-4

GFS





Initialization

24-h Fc

VC = 0.17 in pressure scale,
Using 2x2 and 3x3 avg, and 2x10-4 s-1
Threshold to define non-divergent flow

Future work: evaluating cyclogenesis

Cyclogenetic processes: we propose diagnostics based on the rate of change of the vertically integrated low-level vorticity (viv), between 1000 and 700 hPa, with respect to the maximum viv reached in that simulation. We define this parameter as Deepening Efficiency.

Since the maximum vorticity values reached in a tropical cyclone representation is a function of horizontal resolution, we propose to deal with this problem also in a non-dimensional way by exploring the ratio of viv as a function of time, over the maximum viv reached in a given simulation of a given cyclone at a certain time.

The time rate of change of this ratio indicates the `specific' cyclogenetic capability of that model and is resolution independent.

Summary of TC features that can be seen in operational global models (*GEOS-4, GEOS-5 v2, GFS, ECMWF T511*) observations, 0.25 GEOS-5 with Tokioka

- Horizontal scale ~wind speed comparable to the large-scale environment (300-700 km; 300-700 km; 300-700km)
- Radius of maximum wind (50-300 km; 40-100km; 40-100km)
- Low-level vorticity (10^-3 s-1, 3x10^-3 s-1)
- 850 hPa wind: above 60 m/s, above 100m/s, above 60m/s
- Eye r (25-150km; 10-40km; 25-50km)
- Warm core (0-8 C; 6-12 C; 4-10C)

Conclusions

- Several Global Models provide realistic representation of tropical cyclones
- To infer statistical properties of TC activity, the tropical cyclones should be as realistic as possible
- It is important to assess the quality of the representation in an objective way
- With these and several other diagnostics, computed on a statistically significant sample of modeled cyclones, we plan to be able to assess in a systematic way what can be expected at each resolution, and perhaps suggest what is the optimal resolution (in terms of representation quality and computational costs) for different problems on a variety of time- and spatial scales.